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THE CHEMICAL CHARACTERISTICS OF MINERAL TAILINGS IN THE PROVINCE OF ONTARIO

1979

Ministry of the Environment
Ontario

The Honourable
Keith C. Norton, Q.C.,
Minister

Gérard J. M. Raymond
Deputy Minister

THE

CHEMICAL CHARACTERISTICS

OF

MINERAL TAILINGS

IN THE

PROVINCE OF ONTARIO

1980

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John R. Hawley
Head, Mining and Metallurgy
Waste Systems Planning Section
Waste Management Branch

IMPORTANT NOTE

All Analytical Results
In This Report
Are Expressed As
Parts Per Million
(ppm)

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INTRODUCTION

Known mineral tailings masses in the Province of Ontario cover 24,767 acres (38.7 square miles) and contain 1,077,352,-000 tons of tailings. Currently, active mines generate an additional 100,243 tons of tailings per day.

Several hundred tailings disposal areas exist in Ontario and these range in size from less than two acres to over 1,000 acres. A common size for these tailings areas is from 50 to 300 acres.

To put things in their proper perspective, Ontario has an area of 412,582 square miles. As such, tailings masses cover approximately .01% of the surface of the province although the land actually "disturbed" by mining activities is greater than this figure indicates.

The environmental problems due to abandoned or inadequately maintained tailings areas have been well documented by the Ontario Ministry of the Environment. Relevant documents include the following:

1. "The Problem of Acid Mine Drainage in the Province of Ontario" (1977, 338 pages);
2. "The Use, Characteristics and Toxicity of Mine-Mill Reagents in the Province of Ontario" (1977, 244 pages);
3. "Tailings Disposal - Recommendations for Site Selection (1976, 44 pages);
4. "Mine Waste Control in Ontario" (1977, 241 pages);
5. "Guidelines for Environmental Control in the Ontario Mineral Industry" (1978, 27 pages).

In brief, poorly controlled tailings areas exposed to the atmosphere can give rise to environmental problems which may include one or more of the following:

1. Leaching of contaminants from the tailings with subsequent impairment of downstream areas. Routinely encountered contaminants include undesirable metals, acids, arsenic and radioisotopes.

2. Physical deterioration of a tailings area by natural processes such as erosion. Existing tailings dams and decant structures may be weakened to the point of failure. Upon failure, large volumes of contaminated sediment can be carried to downstream areas. In addition, wind can lift contaminated material from the surface of a tailings mass and transport it long distances.

3. Contamination of local groundwater supplies.

4. Contamination of local vegetation and animal life by processes such as metal uptake and bio-accumulation.

Given the fact that significant acreages and enormous volumes of mineral tailings are available, it is not surprising that many attempts have been made to develop large and small scale uses for waste mineral tailings. In fact, due to the great amount of energy that is required to reduce solid rock to the sandy or silty consistency of tailings, the need to conserve energy supplies and the serious environmental problems that are sometimes created by these deposits, every effort should be made to encourage the re-use of discarded mineral tailings. In addition, in order to help conserve supplies of non-renewable, naturally occurring substances, efforts to win residual mineral values from tailings masses should be encouraged.

In spite of the above statements, some tailings deposits should be regarded as unfit for re-use or as unfit for a particular use due to one or more of a variety of factors. These factors may be physical, chemical, and/or radiological in nature.

The chemical and physical characteristics of any specific tailings deposit depend on the geology and mineralogy of the deposit being mined, the mining method being used and on the milling procedures that are (or were being) followed in order to liberate the required mineral values from the ore. Even within the same mining camp, the chemical and physical characteristics of individual tailings masses often (although not always) vary widely.

Over the years, there have been many notable instances of contaminated discharges from active and abandoned tailings deposits in Ontario. Close examination of these discharges frequently revealed a complex chemical nature that was previously unsuspected.

The intent of this report is to outline, in some detail, the general chemical characteristics of all important tailings deposits now existent in the Province of Ontario. Relevant conclusions are drawn.

Sampling and Analytical Procedures

This report is based on 121 composite samples of tailings that were taken during the Summer and Fall of 1977. These samples represent over 100 different tailings areas in the Province of Ontario. The areas sampled contained an aggregate total of approximately 760,000,000 tons of mineral tailings (70% of all known tonnages in the province).

All samples were analyzed for:

Sodium as Na	Cadmium as Cd
Magnesium as Mg	Tin as Sn
Aluminum as Al	Antimony as Sb
Potassium as K	Boron as B
Calcium as Ca	Barium as Ba
Titanium as Ti	Mercury as Hg
Vanadium as V	Lead as Pb
Chromium as Cr	Bismuth as Bi
Manganese as Mn	Total Kjeldahl Nitrogen as N
Iron as Fe	Chloride as Cl^-
Cobalt as Co	Sulphur and Sulphate as SO_4
Nickel as Ni	Fluorine as F
Copper as Cu	Phosphorus as P
Zinc as Zn	Arsenic as As
Strontium as Sr	Selenium as Se
Molybdenum as Mo	Carbonate as CO_3

The following is a summary of the analytical techniques used during the analysis of the tailings samples and the detection limits associated with these procedures:

Analytical Technique	Analysis	Limit of Detection (ppm)
Atomic Absorption Flame Method	Sodium as Na	0.01
	Magnesium as Mg	0.01
	Aluminum as Al	0.01
	Potassium as K	0.01
	Calcium as Ca	0.01
	Titanium as Ti	0.2
	Vanadium as V	0.06
	Chromium as Cr	0.01
	Manganese as Mn	0.001
	Iron as Fe	0.01
	Cobalt as Co	0.01
	Nickel as Ni	0.01
	Copper as Cu	0.001
	Zinc as Zn	0.01
	Strontium as Sr	0.01
	Molybdenum as Mo	0.03
	Cadmium as Cd	0.001
	Tin as Sn	0.01
	Antimony as Sb	0.1
	Boron as B	0.25
	Barium as Ba	0.1
	Mercury as Hg	0.001
	Lead as Pb	0.02
	Bismuth as Bi	0.04
Total Kjeldahl Nitrogen	Nitrogen	1.0
Titrimetric	Chloride as Cl^-	0.04
Gravimetric	Sulphur as SO_4	1
	Sulphate	1
Photometric	Fluorine as F	0.05
	Phosphorus as P	0.1
	Arsenic as As	0.005
	Selenium as Se	0.0005
Gas Evolution	Carbonate as CO_3	0.1

The "average" analytical results quoted throughout this report are, in general, simple arithmetic averages based on the data available. Whenever and wherever possible, anomalous values were rejected.

The detection limits, as noted above, are defined as the concentrations in aqueous solution which will produce a signal that is twice the standard deviation of the random fluctuations of the background signal and are typical for previous work.

Photometric techniques were used to detect arsenic and selenium because this method has a lower detection limit than the atomic absorption method.

All sulphurous compounds in the samples were oxidized to sulphate during the digestion process and are, therefore, included in the sulphate values recorded.

Samples were solubilized using HCl, HNO_3 and HF under pressure prior to analysis of metals present when using the Atomic Absorption unit. This procedure, which varied from metal to metal, resulted in the complete dissolution of the samples prior to analysis.

Because the analytical work was continually checked by submission of known standards and inter-laboratory cross checks, the precision of the work completed is thought to be better than 95% with a 2% variation between samples for analysis of metals.

Unless otherwise indicated, all analytical results quoted in this report are expressed as parts per million (ppm).

Mineral tailings deposits at both active and abandoned mining sites in Ontario were sampled for the purposes of this report. Several samples represent deposits that were abandoned in the late 1800's or early 1900's.

As a convenience, the analytical results presented in the report have been divided into six fundamental categories:

1. Mineral Tailings: Gold Operations
2. Mineral Tailings: Silver Operations
3. Mineral Tailings: Base Metal Sulphide Operations (Cu, Ni, Pb, Zn)
4. Mineral Tailings: Iron Operations
5. Mineral Tailings: Uranium Operations
6. Mineral Tailings: Others

Corresponding analytical results are reported in Appendices A, B, C, D, E, and F respectively.

GENERAL SUMMARY

(1)

The following "Ontario Average Tailings Analysis" was based on over 3,700 individual chemical results that were, in turn,based on 121 composite samples representing over 100 different tailings areas containing an aggregate total of 760,000,000 tons of tailings:

	Ontario Average Tailings Analysis (ppm)	Average Earths Crust (ppm)
Sodium as Na	13,871	28,300
Magnesium as Mg	9,861	20,900
Nitrogen as N	58	20
Fluorine as F	264	625
Aluminum as Al	29,005	81,300
Phosphorus as P	736	1,050
Chlorine as Cl	Less than 32	130
Potassium as K	14,815	25,900
Calcium as Ca	4,089	36,300
Titanium as Ti	645	4,400
Vanadium as V	178	135
Chromium as Cr	155	100
Manganese as Mn	702	950
Iron as Fe	87,952	50,000
Cobalt as Co	83	25
Nickel as Ni	Less than 214	75
Copper as Cu	310	55
Zinc as Zn	209	70
Arsenic as As	3,034	1.8
Selenium as Se	Less than 3.7	0.05
Strontium as Sr	96	375
Molybdenum as Mo	Less than 1.35	1.5
Cadmium as Cd	2.4	0.2
Tin as Sn	105	2
Antimony as Sb	256	0.2
Boron as B	97	10
Barium as Ba	26	425
Mercury as Hg	Less than .7	0.08
Lead as Pb	66	13
Bismuth as Bi	Less than 17	0.2
Sulphur as S	14,724	260

In the past, tailings masses in the province have been characterized as:

(i) simple sterile soils, and
(ii) rich deposits of almost every metal.

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Chlorine as Cl	Less than 32	130
Potassium as K	14,815	25,900
Calcium as Ca	4,089	36,300
Titanium as Ti	645	4,400
Vanadium as V	178	135
Chromium as Cr	155	100
Manganese as Mn	702	950
Iron as Fe	87,952	50,000
Cobalt as Co	83	25
Nickel as Ni	Less than 214	75
Copper as Cu	310	55
Zinc as Zn	209	70
Arsenic as As	3,034	1.8
Selenium as Se	Less than 3.7	0.05
Strontium as Sr	96	375
Molybdenum as Mo	Less than 1.35	1.5
Cadmium as Cd	2.4	0.2
Tin as Sn	105	2
Antimony as Sb	256	0.2
Boron as B	97	10
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Mercury as Hg	Less than .7	0.08
Lead as Pb	66	13
Bismuth as Bi	Less than 17	0.2
Sulphur as S	14,724	260

In the past, tailings masses in the province have been characterized as:

(i) simple sterile soils, and
(ii) rich deposits of almost every metal.

In reality, neither of the above is strictly true. Compared to the chemistry of the earth's crust, Ontario tailings areas are routinely:

depleted in:
- sodium
- magnesium
- fluorine
- aluminum
- phosphorus
- chlorine
- potassium
- calcium
- titanium
- manganese
- strontium
- barium
- molybdenum

enriched in:
- nitrogen
- vanadium
- chromium
- iron
- cobalt
- nickel
- copper
- zinc
- arsenic
- selenium
- cadmium
- tin
- antimony
- boron
- mercury
- lead
- bismuth
- sulphur

There are, of course, individual exceptions to all cases above.

The causes or probable causes of the enrichments or depletions listed can be explained with relative ease in most cases. Explanations involve concepts of mineralogy-geology and intimate knowledge of mine-mill process technology.

From an environmental standpoint, we are most interested in those mobile elements that commonly occur in tailings areas in above average or abnormal concentrations. With this in mind, the high level of sulphur and arsenic routinely encountered in Ontario tailings areas should be noted. The stresses that can be placed on the environment by these two elements and their associated compounds are well documented. The low level of calcium noted in these tailings areas is also of interest since calcium compounds are, in large part, responsible for the acid neutralizing capacity that any specific tailings mass might have.

On a Province-wide basis, the two most important environmental problems that are likely to be encountered at Ontario tailings disposal sites are the control of:

(1) sulphur and sulphur compounds, and
(2) arsenic and arsenic compounds

(2)

To achieve a proper perspective, the "Ontario Average Tailings Analysis" should be compared to the chemical composition of common rocks such as granite and diabase:

	Ontario Average Tailings Analysis (ppm)	Granite (ppm)	Diabase (ppm)
Sodium as Na	13,871	24,600	15,400
Magnesium as Mg	9,861	2,400	39,900
Nitrogen as N	58	8	14
Fluorine as F	264	700	250
Aluminum as Al	29,005	74,300	78,600
Phosphorus as P	736	390	650
Chlorine as Cl	Less than 32	50	N.A.
Potassium as K	14,815	45,100	5,300
Calcium as Ca	4,089	9,900	78,300
Titanium as Ti	645	1,500	6,400
Vanadium as V	178	16	240
Chromium as Cr	155	22	120
Manganese as Mn	702	230	1,320
Iron as Fe	87,952	13,700	77,600
Cobalt as Co	83	2.4	50
Nickel as Ni	Less than 214	2	78
Copper as Cu	310	13	110
Zinc as Zn	209	45	82
Arsenic as As	3,034	0.8	2.2
Selenium as Se	Less than 3.7	N.A.	N.A.
Strontium as Sr	96	250	180
Molybdenum as Mo	Less than 1.35	7	0.05
Cadmium as Cd	2.4	0.06	0.3
Tin as Sn	105	4	3
Antimony as Sb	256	0.4	1.1
Boron as B	97	2	17
Barium as Ba	26	1,220	180
Mercury as Hg	Less than .7	0.2	0.2
Lead as Pb	66	49	8
Bismuth as Bi	Less than 17	0.1	0.2
Sulphur as S	14,724	175	135

The above data indicates, for instance, that common diabase may routinely contain more:

sodium
magnesium
aluminum
calcium
titanium
vanadium
manganese
strontium
barium

than tailings masses in the Province contain. Similarly, granite is routinely richer in:

sodium
fluorine
aluminum
chlorine
potassium
calcium
titanium
strontium
molybdenum
barium

In fact, the concentrations of substances such as:

sodium
fluorine
phosphorus
vanadium
chromium
iron
cobalt

commonly detected in Ontario tailings masses are roughly comparable to the concentrations of these same substances found in diabase. It should be noted, however, that even the chemical composition of common rocks such as granite and diabase varies quite widely (see Section One of this report) and a number of interpretations of the data presented in this report can be made. Each interpretation may have its own degree of validity.

Again, the high levels of sulphur and arsenic generally found in Ontario tailings masses compared to the levels normally found in common rocks such as granite and diabase can be readily noted.

The Province-wide chemical characteristics of mineral tailings in Ontario mining camps may be summarized as follows:

*Note - a designation such as Lead as Pb low 26
high 1,544

means that within the mining camp referred to, a number of tailings areas averaged 26 ppm lead while another significant group of tailings areas averaged 1,544 ppm lead. The two values could not be combined to give a single realistic value for the camp as a whole.

Mining Camp	Gold	Silver	Base Metal Sulphide (Cu,Ni,Pb,Zn)	Iron
Sodium as Na	12,560	17,581	5,882	7,123
Magnesium as Mg	8,615	9,669	13,909	11,135
Nitrogen as N	56	45	34	23
Fluorine as F	256	275	297	235
Aluminum as Al	29,686	30,448	23,532	17,975
Phosphorus as P	788	840	351	495
Chlorine as Cl	26	<15	25	<14
Potassium as K	12,397	9,702	8,310	11,045
Calcium as Ca	4,020	4,686	3,348	4,375
Titanium as Ti	219	952	891	701
Vanadium as V	131	199	171	133
Chromium as Cr	116	195	142	105
Manganese as Mn	672	849	800	680
Iron as Fe	49,647	53,836	126,781	120,000
Cobalt as Co	21	395	87	8
Nickel as Ni	65	178	low <37 high 2,812	146
Copper as Cu	87	211	664	40
Zinc as Zn	138	211	low 171 high 3,685	62
Arsenic as As	low 356 high 5,317	5,970	276	124
Selenium as Se	<2.4	<1.7	<43	6
Strontium as Sr	98	45	79	98
Molybdenum as Mo	<1.3	1.3	<1.3	<0.6
Cadmium as Cd	1.8	1.4	4.5	1.4
Tin as Sn	98	68	148	79
Antimony as Sb	254	226	222	168
Boron as B	92	88	90	173
Barium as Ba	20	25	28	20
Mercury as Hg	0.4	1.2	0.1	0.03
Lead as Pb	low 26 high 1,544	64	82	13
Bismuth as Bi	11	22	28	23
Sulphur as S	10,706	4,804	27,831	9,373
Carbonate as CO_3	7,616	7,102	<1,865	<1,000

The above information can be used to draw general conclusions concerning the relative abundance of specific elements as they occur in tailings masses generated by broad categories of mineral extraction industries in the Province. For instance, it would appear that, in Ontario, arsenic levels are highest in tailings resulting from silver mining activities and lowest in tailings resulting from iron mining operations. However, this does not necessarily mean that environmental problems due to arsenic are most severe at Ontario silver mining sites and non-existent at Ontario iron mining operations. The chemical form that an element takes quite often varies considerably from camp to camp. High levels of an element in its most insoluble form in one camp may generate no environmental problems at all while low levels of that same element in a very soluble form in another camp may give rise to severe environmental problems.

TYPICAL CHEMICAL CHARACTERISTICS OF

MINERAL TAILINGS IN ONTARIO GOLD CAMPS

Gold Camp	Pickle L. Central Patricia	Geraldton-Beardmore	Uchi L. Confed. L.	Mata-chewan Area
Sodium as Na	4,021	14,090	9,960	23,550
Magnesium as Mg	14,933	6,954	9,595	4,178
Nitrogen as N	34	72	low 5.8 high 373	42
Fluorine as F	192	207	252	291
Aluminum as Al	15,933	30,450	24,050	54,025
Phosphorus as P	low 272 high 1,952	1,352	482	818
Chlorine as Cl	26	27	19	23
Potassium as K	4,350	11,033	13,800	57,350
Calcium as Ca	5,022	3,985	4,955	2,883
Titanium as Ti	214	180	low 220 high 1,580	183
Vanadium as V	108	137	123	125
Chromium as Cr	96	127	107	100
Manganese as Mn	824	463	701	481
Iron as Fe	low 53,875 high 223,800	52,871	61,400	32,600
Cobalt as Co	12	16	23	7
Nickel as Ni	<22	195	low <10 high 365	low 71 high 303
Copper as Cu	122	79	74	low 24 high 166
Zinc as Zn	182	120	181	low 84 high 1,000
Arsenic as As	low 337 high 5,664	8,852	low 58 high 525	292
Selenium as Se	<4	<1	<1	<2
Strontium as Sr	49	128	83	60
Molybdenum as Mo	<0.6	<0.6	0.9	<0.7
Cadmium as Cd	2	1.9	1.4	1.7
Tin as Sn	170	111	90	56
Antimony as Sb	363	187	214	208
Boron as B	101	93	102	87
Barium as Ba	24	24	25	30
Mercury as Hg	0.222	0.672	0.269	0.086
Lead as Pb	43	low 3.8 high 35	11	low 17 high 1,010
Bismuth as Bi	<10	<10	<10	<12
Sulphur as S	15,249	4,258	4,542	12,642
Carbonate as CO_3	<1,629	17,000	14,400	low 9,000 high 45,000

TYPICAL CHEMICAL CHARACTERISTICS OF

MINERAL TAILINGS IN ONTARIO GOLD CAMPS

Gold Camp	Timmins Area	Kirkland & Larder Lakes	Red Lake	Wawa-Missanabie
Sodium as Na	5,076	18,100	low 1,662 high 20,760	13,123
Magnesium as Mg	10,348	7,333	11,229	4,353
Nitrogen as N	62	60	31	88
Fluorine as F	230	305	327	247
Aluminum as Al	23,630	30,743	32,278	26,375
Phosphorus as P	464	956	542	899
Chlorine as Cl	21	low 14 high 140	41	25
Potassium as K	12,504	low 6,888 high 40,875	14,258	18,438
Calcium as Ca	5,427	3,245	3,889	2,750
Titanium as Ti	100	318	726	320
Vanadium as V	148	194	117	99
Chromium as Cr	156	140	71	133
Manganese as Mn	801	671	940	496
Iron as Fe	51,464	45,236	47,760	56,200
Cobalt as Co	28	27	22	31
Nickel as Ni	70	low 35 high 304	93	<34
Copper as Cu	low 71 high 1,371	98	59	91
Zinc as Zn	low 169 high 3,110	94	162	89
Arsenic as As	1,668	low 249 high 6,225	4,176	672
Selenium as Se	3.5	low 2.1 high 11	2.4	<3
Strontium as Sr	38	221	80	124
Molybdenum as Mo	<0.6	4	<1.1	1.6
Cadmium as Cd	4	0.8	1.8	0.8
Tin as Sn	89	103	67	98
Antimony as Sb	329	192	309	232
Boron as B	91	84	99	81
Barium as Ba	14	13	17	13
Mercury as Hg	0.166	1.03	0.287	0.417
Lead as Pb	low 25 high 2,078	23	25	32
Bismuth as Bi	<14	<11	<10	<10
Sulphur as S	12,901	15,312	11,533	9,210
Carbonate as CO_3	low 2,500 high 47,400	8,200	3,333	<4,867

The above information can be used to draw general conclusions concerning the relative abundance of specific elements as they occur in tailings deposits located in and around specific Ontario gold mining camps. For instance, mercury concentrations appear to be highest in tailings areas in the Kirkland Lake & Larder Lake gold camps and lowest in the Matachewan gold area. However, the form in which the mercury occurs has not been defined. In most cases, the mercury is probably present as traces of mercury sulphide. However, some (not all) gold operations use metallic mercury during milling operations and the possibility exists that very small amounts of metallic mercury could find its way into the tailings areas serving these operations.

TYPICAL CHEMICAL CHARACTERISTICS OF

MINERAL TAILINGS IN ONTARIO SILVER CAMPS

Silver Camp	Cobalt Area	Gowganda Area
Sodium as Na	27,113	8,050
Magnesium as Mg	9,113	10,225
Nitrogen as N	48	42
Fluorine as F	257	292
Aluminum as Al	40,995	19,900
Phosphorus as P	1,155	524
Chlorine as Cl	<13	17
Potassium as K	8,779	10,625
Calcium as Ca	4,406	4,965
Titanium as Ti	1,038	866
Vanadium as V	216	181
Chromium as Cr	151	238
Manganese as Mn	644	1,054
Iron as Fe	50,121	57,550
Cobalt as Co	426	363
Nickel as Ni	166	190
Copper as Cu	309	112
Zinc as Zn	314	107
Arsenic as As	4,275	7,665
Selenium as Se	<1.3	2
Strontium as Sr	59	30
Molybdenum as Mo	<1.1	1.4
Cadmium as Cd	1.5	1.2
Tin as Sn	74	61
Antimony as Sb	267	185
Boron as B	95	81
Barium as Ba	34	15
Mercury as Hg	1.335	0.972
Lead as Pb	101	27
Bismuth as Bi	26	18
Sulphur as S	4,247	5,361
Carbonate as CO_3	5,203	9,000

TYPICAL CHEMICAL CHARACTERISTICS OF MINERAL

TAILINGS IN ONTARIO BASE METAL SULPHIDE CAMPS

Base Metal Sulphide Camp	Timmins Kirkland Lake Areas	S. S. Marie Sudbury Temagami Areas	Manitou-wadge Area	North Western Ontario Areas
Sodium as Na	2,413	9,141	7,385	4,590
Magnesium as Mg	17,358	12,650	8,915	16,713
Nitrogen as N	47	30	25	33
Fluorine as F	224	275	376	314
Aluminum as Al	24,315	27,521	28,600	13,693
Phosphorus as P	220	443	325	414
Chlorine as Cl	17	<15	25	41
Potassium as K	8,145	8,429	12,700	3,967
Calcium as Ca	3,102	4,612	1,742	3,936
Titanium as Ti	539	1,323	845	856
Vanadium as V	98	194	<40	351
Chromium as Cr	114	249	49	157
Manganese as Mn	636	676	612	1,276
Iron as Fe	153,500	89,127	116,500	148,000
Cobalt as Co	90	80	12	165
Nickel as Ni	64	1,983	<10	3,640
Copper as Cu	639	519	834	8,220
Zinc as Zn	2,789	164	4,580	177
Arsenic as As	667	232	97	108
Selenium as Se	63	8	<58	41
Strontium as Sr	126	103	61	26
Molybdenum as Mo	2.5	<1	<0.6	1
Cadmium as Cd	8	2.3	4.7	3
Tin as Sn	137	125	180	149
Antimony as Sb	196	292	180	221
Boron as B	93	86	103	76
Barium as Ba	34	27	26	24
Mercury as Hg	0.262	0.057	0.037	0.075
Lead as Pb	44	26	249	10
Bismuth as Bi	43	14	<10	43
Sulphur as S	47,019	22,427	13,844	28,034
Carbonate as CO_3	<1,250	<3,877	<1,000	1,333

TYPICAL CHEMICAL CHARACTERISTICS OF

MINERAL TAILINGS IN ONTARIO IRON MINING AREAS

Iron Mining Area	North Eastern Ontario	North Western Ontario
Sodium as Na	2,845	11,400
Magnesium as Mg	16,050	6,220
Nitrogen as N	4.2	41.8
Fluorine as F	122	347
Aluminum as Al	12,750	23,200
Phosphorus as P	392	598
Chlorine as Cl	<10	17
Potassium as K	3,290	18,800
Calcium as Ca	5,490	3,260
Titanium as Ti	72	1,330
Vanadium as V	180	85
Chromium as Cr	130	79
Manganese as Mn	1,053	306
Iron as Fe	95,400	145,000
Cobalt as Co	10	6
Nickel as Ni	253	38
Copper as Cu	40	39
Zinc as Zn	85	39.5
Arsenic as As	190	58
Selenium as Se	<1	10
Strontium as Sr	71	124
Molybdenum as Mo	<0.6	<0.6
Cadmium as Cd	1.2	1.5
Tin as Sn	85	73
Antimony as Sb	144	191
Boron as B	265	81
Barium as Ba	29	10
Mercury as Hg	0.044	<0.005
Lead as Pb	14	11
Bismuth as Bi	<10	35
Sulphur as S	12,433	6,313
Carbonate as CO_3	<1,000	<1,000

TYPICAL CHEMICAL CHARACTERISTICS OF MINERAL TAILINGS IN ONTARIO URANIUM MINING AREAS

Uranium Camp	Bancroft Camp	Elliot Lake Camp
Sodium as Na	31,300	1,170
Magnesium as Mg	4,550	783
Nitrogen as N	36	75.4
Fluorine as F	1,292	225
Aluminum as Al	29,033	19,600
Phosphorus as P	634	48
Chlorine as Cl	23	10
Potassium as K	31,533	28,000
Calcium as Ca	1,814	97.8
Titanium as Ti	1,678	97
Vanadium as V	119	40
Chromium as Cr	109	20
Manganese as Mn	759	<10
Iron as Fe	36,090	11,100
Cobalt as Co	7	<1
Nickel as Ni	76	<10
Copper as Cu	36	39
Zinc as Zn	125	9.8
Arsenic as As	369	137
Selenium as Se	<1	<1
Strontium as Sr	139	21
Molybdenum as Mo	1.3	2.7
Cadmium as Cd	1	0.3
Tin as Sn	86	18
Antimony as Sb	118	97
Boron as B	101	107
Barium as Ba	21	205
Mercury as Hg	0.039	-
Lead as Pb	72	23
Bismuth as Bi	11	<10
Sulphur as S	6,481	4,676
Carbonate as CO_3	<1,000	<1,000

NOTE: The data presented here is considered to be representative for the Bancroft uranium camp. However, the Elliot Lake camp data is based on only one tailings sample and, as such, is not thought to be truly representative of the entire camp.

In a strictly theoretical sense, there are few, if any, substances in the universe that can truly be described as "inert." Sooner or later, even the most resistant substances are conquered by the forces of their environment. Taking this point of view, all the materials found in a tailings area are eventually free to escape the area. The most essential ingredient in this type of approach is the element of time. In most cases, the time required for the dissolutions or reactions to go to completion approximates that of hundreds or thousands of human life spans. On a day-to-day, or short-term basis, this approach to environmental problems generated by existing deposits of mineral tailings is not practical except perhaps in a few instances such as those involving specific long-lived radio-isotopes.

In the brief discussions that follow, concerning the environmental impact of individual metals found in Ontario tailings areas, the approach taken is practical and not theoretical. It is recognized that over periods of hundreds or hundreds of thousands of years, most components of a tailings area including the mineral silicates will undergo some degree of chemical or physical change. However, most common components of the earth's crust will also undergo similar changes given the same physical and chemical conditions. In this context, the use of the words "stable" or "inert" in this section involves short-term time concepts (tens or hundreds of years as opposed to thousands or hundreds of thousands of years) and chemical and/or physical reactions that, for all intents and purposes occur with imperceptible slowness.

A detailed explanation of the following data is found in Section C of this report.

(1)

Aluminum

Aluminum levels in Ontario tailings areas range from 1,660 ppm to 95,700 ppm and average 29,005 ppm. Almost all of this aluminum occurs in stable compounds which include complex silicates. Since the earth's crust commonly contains nearly three times as much aluminum as Ontario tailings areas and the chemical compounds involved are largely common to both, it would appear to follow that aluminum does not present an environmental hazard at most Ontario tailings areas.

(2)

Antimony

Antimony levels in Ontario tailings areas range from less than 10 ppm to 1,590 ppm and average 256 ppm. Since the earth's crust commonly contains approximately .2 ppm antimony, this substance could present environmental problems under specific conditions. Also, in Ontario, antimony commonly occurs in combination with sulphur. Sulphur-metal combinations, from an environmental standpoint, are considered to be unstable.

To date, antimony has not been identified as a major environmental problem at any Ontario mining site.

(3)

Arsenic

Arsenic levels in Ontario tailings areas range from less than 20 ppm to 75,400 ppm and average 3,034 ppm. Since the average level of arsenic in the earth's crust is approximately 1.8 ppm and in view of the fact that most arsenic compounds encountered in Ontario tailings areas are reactive and/or slightly soluble in water, major environmental problems can be routinely expected to occur in most areas where arsenic levels are abnormally high.

Arsenic problems are commonly encountered in Ontario gold and silver mining camps.

(4)

Barium

Barium levels in Ontario tailings areas range from 5 ppm to 313 ppm and average 26 ppm. Barium levels in the earth's crust are thought to average 425 ppm. Since most barium compounds routinely encountered in Ontario tailings areas are relatively stable, environmental problems due to barium are not normally expected.

(5)

Bismuth

Bismuth levels in Ontario tailings areas range from less than 10 ppm to 2,020 ppm and average less than 17 ppm. On the average, the earth's crust contains .2 ppm bismuth. In Ontario, bismuth commonly occurs in combination with sulphur and, as such, must be regarded as a potential problem. Problems, when and if they do occur, are most likely in areas where massive base metal sulphides are mined.

To date, bismuth has not been identified as a major environmental problem at any mining site in Ontario.

(6)

Boron

Boron levels in Ontario tailings areas range from 2 ppm to 435 ppm and average 97 ppm. Since natural levels of boron in the earth's crust only approximate 10 ppm, it would be normally assumed that boron is a potential environmental problem in Ontario tailings areas. Fortunately, however, boron in these areas occurs, for the most part, in the form of a very stable mineral called tourmaline,

$$(Na, Ca)(Li, Mg, Fe^{++}, Al)_3(Al, Fe^{+++})_6 B_3 Si_8 O_{27} (O, OH, F)_4$$

It is highly unlikely, therefore, that boron constitutes a serious problem at existing tailing deposits in Ontario.

(7)

Cadmium

Cadmium levels in Ontario tailings areas range from .3 ppm to 155 ppm and average 2.4 ppm. The earth's crust, on the average, is said to contain approximately .2 ppm cadmium. At first glance and due to the rough similarity in the above cadmium concentrations (tailings vs. earth's crust) one might assume that major environmental problems due to the cadmium content of Ontario tailings masses are possible but not probable. Other significant factors must, however, be noted. Of most importance is the fact that cadmium can and does enter into the zinc sulphide (sphalerite) crystal structure and this mineral (sphalerite) is one of the most common minerals mined in the Province. Of almost equal importance is the fact that sphalerite in Ontario is almost always associated with massive base metal sulphide deposits and tailings resulting from the processing of these deposits routinely give rise to a very undesirable environmental condition termed acid mine drainage. The data contained in this report indicates that cadmium concentrations in tailings resulting from massive base metal sulphide operations contain, on the average, at least two and one-half times the cadmium found in other types of tailings.

Since these base metal sulphide tailings are routinely quite reactive (highly unstable), under appropriate conditions, cadmium can give rise to serious environmental problems.

In Ontario, environmental problems due to cadmium have been noted at a number of base metal sulphide mining properties.

It should be emphasized that cadmium in these areas is associated specifically with zinc sulphide and not with zinc in general.

(8)

Calcium

Calcium levels in Ontario tailings areas range from 98 ppm to 15,300 ppm and average 4,089 ppm. The earth's crust is said to contain an average of 36,300 ppm calcium. Calcium in Ontario tailings areas occurs predominantly in the form of complex silicates with lesser amounts occurring in carbonates and sulphates.

Calcium does not present an environmental hazard in Ontario tailings areas.

(9)

Chlorine

Chlorine levels in Ontario tailings areas range from less than 10 ppm to 380 ppm and average less than 32 ppm. The earth's crust is said to contain approximately 130 ppm chlorine. Most of the chlorine in Ontario tailings areas is thought to occur in stable minerals such as sodalite,

$$(Na_4\ Al_3\ O_{12}\ Cl)$$

and chlorapatite,

$$Ca_2\ (PO_5)_3\ Cl$$

Chlorine does not present an environmental hazard in Ontario tailings areas.

(10)

Chromium

Chromium levels in Ontario tailings areas range from 19 ppm to 1,040 ppm and average 155 ppm. Average chromium levels in the earth's crust approximate 100 ppm.

In Ontario tailings areas, chromium occurs in stable minerals such as chromite,

$$(Mg, Fe^{\cdot\cdot})(Cr, Al, Fe^{\cdot\cdot})_2 O_4$$

Chromium does not normally present environmental problems in Ontario tailings areas although small quantities of the metal have been detected in acid drainage flows.

(11)

Cobalt

Cobalt levels in Ontario tailings areas range from less than 1 ppm to 4,060 ppm and average 83 ppm. Average cobalt levels in the earth's crust are reported to be 25 ppm. In Ontario, cobalt routinely occurs in various combinations with arsenic and sulphur. The reactive nature of these compounds indicates that environmental problems involving cobalt are possible at Ontario tailings areas assuming appropriate conditions exist.

To date, minor quantities of cobalt have been encountered in seepage flows from a few Ontario properties.

(12)

Copper

Copper levels in Ontario tailings areas range from less than 10 ppm to 18,700 ppm and average 310 ppm. Copper levels in the earth's crust are reported to average approximately 55 ppm.

In Ontario, copper is almost always found in combination with sulphur. As a result, environmental problems due to copper contained in Ontario tailings areas are relatively common and, in particular, are very common at base metal sulphide properties.

(13)

Fluorine

Fluorine levels in Ontario tailings areas range from 78 to 2,520 ppm and average 264 ppm. Fluorine concentrations in the earth's crust are said to average approximately 625 ppm. Much of the fluorine in igneous rocks is in the form of fluorapatite,

$$Ca_5 (PO_4)_3 F$$

Fluorite, $Ca F_2$, is also common.

To date, fluorine is not considered to be a major environmental problem at tailings areas in Ontario.

(14)

Iron

Iron levels in Ontario tailings areas range from 2,770 ppm to 375,000 ppm and average 87,952 ppm. The average iron content of the earth's crust is approximately 50,000 ppm.

In many tailings areas, iron occurs in the form of stable silicates and oxides and presents no significant documented environmental problems. In a few rare instances, iron in Ontario tailings areas occurs as a relatively soluble carbonate and isolated environmental problems of questionable significance have been noted.

In a great many tailings deposits in Ontario, large quantities of iron occur in the form of sulphides (pyrite, pyrrhotite, marcasite). From an environmental standpoint, iron/sulphur compounds are extremely unstable and in a great many instances give rise to the very serious problem called "acid mine drainage."

(15)

Lead

Lead levels in Ontario tailings areas range from less than 1 ppm to 6,900 ppm and average 66 ppm. The earth's crust contains approximately 13 ppm lead.

While occurring in a large number of rock-forming minerals, most lead in Ontario tailings areas occurs with sulphur in the form of galena (PbS). Because of the unstable nature (from an environmental standpoint) of most sulphur-metal compounds, major environmental problems due to lead could reasonably be suspected at a great number of Ontario tailings areas. In fact, however, lead concentrations in waste flows originating at Ontario tailings areas rarely exceed .5 ppm. This is largely due to the physical and chemical properties of lead and its compounds. A trend towards the formation of insoluble or sparingly soluble compounds is frequently noted.

(16)

Magnesium

Magnesium levels in Ontario tailings areas range from 98 ppm to 36,600 ppm and average 9,861 ppm. The earth's crust is said to average 20,900 ppm magnesium.

In Ontario tailings areas, magnesium is commonly tied up in simple or complex stable silicates with lesser amounts occurring as carbonates and oxide/hydroxide-type compounds.

Magnesium is not considered to be an environmental problem at Ontario tailings disposal areas.

(17)

Manganese

Manganese levels in Ontario tailings areas range from less than 10 ppm to 2,870 ppm and average 702 ppm. The average manganese content of the earth's crust is stated to be approximately 950 ppm.

Manganese occurs as a trace or minor element in a variey of minerals including silicates. The most common manganese mineral appears to be pyrolusite ($Mn\ O_2$).

In Ontario, waste flows originating at active and abandoned mineral tailings areas that produce acid (acid mine drainage) commonly exhibit reasonably high levels of manganese (5 to 10 ppm) (in one case, acid mine water was found to contain 83 ppm manganese). At most other (non-acid) tailings areas, manganese levels are low.

To date, in Ontario, manganese has not been diagnosed as a serious environmental problem originating at tailings areas. However, caution should be exercised when any metal in its dissolved form exceeds 1 ppm in any waste flow. On this basis, manganese is a potential problem.

(18)

Mercury

Mercury levels in Ontario tailings areas range from less than .005 ppm to 2,350 ppm and average less than .7 ppm. Mercury levels in the earth's crust may approximate .08 ppm to .5 ppm.

In Ontario, mercury levels appear to be highest in tailings in the silver mining areas (1.2 ppm), moderate in gold tailings areas (.4 ppm), lower in base metal sulphide tailings (.1 ppm) and lowest in tailings resulting from iron (taconite) operations (.03 ppm).

In most cases, mercury in a tailings area will occur as the sulphide or, at least, in combination with sulphur. In a few cases, metallic mercury may be present. It should be noted that some (not all) gold operations in Ontario use metallic mercury to assist in the recovery of gold from its ore.

Mercury is noted for the environmental stresses that it can create. Therefore, the presence of mercury in any tailings area is worthy of note.

High mercury concentrations are not normally encountered in Ontario mine-mill effluents. At designated control points, Ontario mine-mill effluents routinely contain less than .2 parts per billion mercury although infrequent excursions into the 1 - 10 parts per billion range have been noted. The above data includes all Ontario gold mills using mercury during milling procedures. In only one case, in 1970, a gold mill using mercury reported an effluent mercury concentration, over a short period of time, of 33 parts per billion. Over a recent three year period, this same operation reported an average (mercury) effluent concentration of .12 parts per billion. At those mills employing mercury to recover gold, metallic mercury losses are reported to be approximately .0014 lbs./ton ore. Not all of this reports to the tailings area.

(19)

Molybdenum

Molybdenum levels in Ontario tailings areas range from less than 0.6 ppm to 3,416 ppm and average less than 1.35 ppm. The average molybdenum content of the earth's crust is stated to be approximately 1.5 ppm.

Molybdenum occurs most commonly as the sulphide MoS_2 (molybdenite). Due to the low concentrations normally encountered in Ontario tailings areas, molybdenum, to date, has not been observed to be an environmental problem. In more significant concentrations, however, because of its relationship with sulphur, molybdenum does have the potential to become an environmental problem.

(20)

Nickel

Nickel levels in Ontario tailings areas range from less than 10 ppm to 10,000 ppm and average less than 214 ppm. The average nickel content of the earth's crust is stated to be approximately 75 ppm. In Ontario tailings areas, nickel is routinely associated with unstable sulphur compounds. As a result, environmental problems due to the nickel content of Ontario tailings areas are relatively common and, in particular, are very common at base metal sulphide properties.

(21)

Nitrogen

Nitrogen levels in Ontario tailings areas range from less than 2.8 ppm to 373 ppm and average 58 ppm. Nitrogen levels in the earth's crust are stated to be approximately 20 ppm.

Abnormal nitrogen levels in Ontario tailings areas, when noted, are usually due to the presence of extraneous materials such as residual mill reagents.

In general, nitrogen does not present an environmental hazard at Ontario tailings areas.

(22)

Phosphorus

Phosphorus levels in Ontario tailings areas range from 38 ppm to 12,300 ppm and average 736 ppm. The earth's crust is said to contain approximately 1,050 ppm phosphorus.

Phosphorus usually occurs in Ontario tailings areas as the minerals fluorapatite $Ca_5(PO_4)_3F$ and chlorapatite $Ca_5(PO_4)_3Cl$.

Phosphorus is not normally considered to be an environmental hazard in Ontario tailings areas.

(23)

Potassium

Potassium levels in Ontario tailings areas range from 489 ppm to 72,000 ppm and average 14,815 ppm. The earth's crust is said to contain approximately 25,900 ppm potassium. Most potassium in Ontario tailings areas is found in the form of relatively stable complex silicates such as:

potash feldspar	$KAlSi_3O_8$
leucite	$KAlSi_2O_6$
Micas	$K(AlSi_3O_{10})Al_2(OH,F)_2$

Potassium is not normally an environmental problem at Ontario tailings areas.

(24)

Selenium

Selenium levels in Ontario tailings areas range from less than 1 ppm to 100 ppm and average less than 3.7 ppm. The average selenium content of the earth's crust is said to be approximately .05 ppm.

Selenium is usually associated with sulphur and/or sulphides. Hence, relatively high levels of selenium have been detected in some Ontario tailings areas. Because of its toxicity and due to the relatively unstable nature of the sulphides with which it commonly occurs, selenium must be regarded as a potential environmental hazard at those tailings areas where abnormal (above background) selenium concentrations have been detected.

(25)

Sodium

Sodium levels in Ontario tailings areas range from 693 ppm to 68,900 ppm and average 13,871 ppm. The earth's crustal average approximates 28,300 ppm.

Almost all of the sodium contained in Ontario tailings areas occurs in stable complex silicate minerals and therefore presents no environmental problems. In at least one rare case, however, halite (NaCl) was observed in fairly large quantities in the ore at one Ontario base metal sulphide property.

(26)

Strontium

Strontium levels in Ontario tailings areas range from 5 ppm to 439 ppm and average 96 ppm. The earth's crust is said to contain approximately 375 ppm strontium.

At the present time, strontium does not appear to be an environmental hazard at Ontario tailings areas.

(27)

Sulphur

Sulphur levels in Ontario tailings areas range from 921 ppm to 106,144 ppm and average 14,724 ppm. Sulphur levels in the earth's crust approximate 260 ppm.

Most of the sulphur in Ontario tailings areas occurs in the form of sulphides and many of these substances are relatively unstable. Major environmental problems due to sulphur have been documented at a variety of mining properties across the province.

(28)

Tin

Tin levels in Ontario tailings areas range from 3 ppm to 336 ppm and average 105 ppm. The earth's crust contains approximately 2 ppm tin.

Some, if not most, of the tin in Ontario tailings areas occurs as small grains of SnO_2 which may occur - 1. individually, or 2. trapped in other minerals (e.g. sulphides).

At the present time, tin does not present a significant environmental problem at Ontario tailings areas.

(29)

Titanium

Titanium levels in Ontario tailings areas range from less than 10 ppm to 2,650 ppm and average 645 ppm. Average titanium levels in the earth's crust approximate 4,400 ppm.

The most common titanium minerals occurring in Ontario tailings masses are ilmenite $FeTiO_3$ and rutile TiO_2. These minerals are relatively stable.

Titanium has been detected in acid wastewater flows from a number of properties in the Province but, in general, significant environmental problems due to titanium have not been noted.

(30)

Vanadium

Vanadium levels in Ontario tailings areas range from 22 ppm to 1,350 ppm and average 178 ppm. The earth's crust is stated to contain approximately 135 ppm vanadium.

In general, vanadium levels in Ontario tailings areas tend to increase with increasing iron concentration.

Vanadium in Ontario tailings areas has, to date, not been noted as a significant environmental problem. However, elevated levels of vanadium have been detected in acid wastewater flows from some Ontario base metal properties.

(31)

Zinc

Zinc levels in Ontario tailings areas range from less than 10 ppm to 46,300 ppm and average 209 ppm. The concentration of zinc in the earth's crust is stated to be approximately 70 ppm.

Zinc in Ontario tailings areas occurs predominantly in the form of ZnS (sphalerite) which routinely occurs in masses of mixed sulphides. From an environmental standpoint, these sulphide assemblages are unstable. As a result, zinc has given rise to significant environmental problems at a number of Ontario tailings disposal sites.

SECTION A

NATURAL LEVELS OF THE CHEMICAL ELEMENTS IN:

(A) THE EARTH'S CRUST

(B) COMMONLY OCCURRING ROCKS

(C) SOILS

The data contained in Appendices A,B,C,D,E and F of this report must be compared to similar data outlining the natural levels of chemical elements in the earth's crust, in commonly occurring rock masses and in soils in order to be useful. There are different ways of obtaining these natural (mean) values and they include:

1. Arithmetic mean of a great number of individual analyses: e.g. CLARKE (1924) determined the mean from about 6,000 analyses of the most different types of rock.
2. Determination of the individual elements in an artificial mixture of the most abundant eruptive rocks (e.g. B.I. and W. NODDACK, 1930, 1934; HEVESY, 1930 and 1932; GOLDSCHMIDT, 1938; VOGT, 1931).
3. Calculation on the basis of mean contents of elements in individual types of rock of the lithosphere, taking into consideration their relative abundance (Table 87).

(A) THE EARTH'S CRUST

Table 87. The Average Composition of the Earth's Crust Assumed by Various Authors

(from FLEISCHER and CHAO, 1960)

Author	Average Composition of the Earth's Crust
POLDERVAART (1955) (up to 40 km depth)	granodiorite 40.8 mass-% diorite & andesite 10.3 mass-% basalt & tholeiite 48.9 mass-%
VINOGRADOV (1962) (applies especially to continental regions of the earth)	acid: basic rock = 2:1
SMITH (taking the ocean basins into consideration)	acid: basic rock = 1:2

Table 88. Distribution in Percent of the Most Important Igneous Rocks in the Lithosphere(from FLEISCHER and CHAO, 1960).

	I.[1]) VOGT (1931)	II.	III. ENGLEHARDT (1936)	IV. DALY (1914)
Granite	50	60	34	36.1
Charnockite	-	-	5	-
Quartzmonzonite & Granodiorite	10	9	-	36.6(granodiorite)
Quartzdiorite & Diorite	8	6	39(diorite)	3.2
Gabbro	18	15	18	22.8
Anorthosite	4	3		
Pyroxenite & Peridotite	0.5	0.25	0.25	0.5
Alkali-lime Syenite	3	2	3(syenite)	0.6
Monzonite	4	3	-	-
Nepheline Syenite	1	0.5	0.5	0.2
Nordmarkite & Pulaskite	1	1	-	-
Essexite and the like	0.5	0.25	-	-
Alkali-Gabbro	-	-	0.25	0.04

[1]) I. on the basis of the conditions given in Norway; II. and III. rough estimate; IV. the data given by DALY which were summarised by FLEISCHER and CHAO (1960).

Table 89. Relative Distribution of Sedimentary Rocks in the Lithosphere

	CLARKE(1924)	Data from ENGELHARDT(1936)
Argillaceous shales, clays	80%	79.6%
Sandstones	15%	11.9%
Limestones	5%	8.1%
Dolomites		0.4%

The quantitative distribution of the chemical elements in nature and hence in the earth's crust is rather uneven, though it follows certain laws.

This pronounced uneven distribution is clearly mirrored by the so-called decadic system, a representation introduced by FERSMAN and shown in Table 91 in condensed form. The regularities of this uneven distribution are caused by internal and external migration factors and are due to the atomic structure of the chemical elements and their positions in the periodic system.

Table 91. "Decadic System" of Distribution of the Chemical Elements (according to VERNADSKII)
(the Clarke values used are rounded off)

100-10%	10-1%	1-0.1%	1,000-100 ppm	100-10 ppm	10 - 1 ppm	1 - 0.1 ppm	0.1 - 0.01 ppm	0.01 - 0.001 ppm	<0.001 ppm
O 47.0	Al 8.1	Ti 0.5	P 930	V 90	Gd 9	Lu 0.8	Hg 0.08	Pt 0.005	Re
Si 29.1	Fe 4.7	Mn 0.1	H 700	Cr 83	Sm 9	Sb 0.5	Ag 0.07	Au 0.004	Xe
	Ca 3.0		F 660	Zn 83	U 4	I 0.4	Se 0.05	Te 0.001	Ra
	K 2.5		Ba 650	Ce 70	Ta 3	In 0.3	Ar 0.04	He 0.001	Rn
	Na 2.5		S 470	Ni 58	Hf 3	Tm 0.3	Pd 0.01	Re 0.001	
	Mg 1.9		Sr 340	Cu 47	Sn 3	Cd 0.1	Bi 0.01	Ir 0.001	
			C 230	Li 32	Br 3			Rh 0.001	
			Cl 170	Y 29	Cs 3			Os 0.001	
			Zr 170	Nb 20	Be 2			Ru 0.001	
			Rb 150	Ga 19	As 2				
				N 19	Eu 1				
				Co 18	Ge 1				
				Pb 16	Tl 1				
				Th 13	Mo 1				
				B 12	W 1				
				and others	and others				
Σ 76.1%	22.7%	0.6%	4,670ppm	685ppm	~ 70ppm	~3ppm	~ 0.3ppm	~0.02ppm	<0.001 ppm

NOTE: Clarke values represent the average abundance of (specific) chemical elements in the whole lithosphere.

Table 92. Clarke Values (ppm) According to Data from Several Authors (The dashes mean that data are not available)

Symbol	CLARKE & WASHINGTON (1924)	FERSMAN (1933 to 1939)	GOLDSCHMIDT (1937)	VINOGRADOV (1949)	(1962)	TAYLOR (1964)
Ac	-	-	-	$x.10^{-10}$	-	-
Ag	0.0X	0.1	0.02	0.1	0.07	0.07
Al	75,100	74,500	81,300	88,000	80,500	82,300
Ar	-	4	-	-	-	-
As	X	5	5	5	1.7	1.8
Au	0.00X	0.005	0.001	0.005	0.004	0.004
B	10	50	10	3	12	10
Ba	470	500	430	500	650	425
Be	10	4	6	6	3.8	2.8
Bi	0.0X	0.1	0.2	0.2	0.009	0.
Br	X	10	2.5	1.6	2.1	2.5
C	870	3,500	320	1,000	230	200
Ca	33,900	32,500	36,300	36,000	29,600	41,500
Cd	0.X	5	0.18	5	0.13	0.2
Ce	-	29	41.6	45	70	60
Cl	1,900	2,000	480	450	170	130
Co	100	20	40	30	18	25
Cr	330	300	200	200	83	100
Cs	0.00X	10	3.2	7	3.7	3
Cu	100	100	70	100	47	55
Dy	-	7.5	4.47	4.5	5	3.0
Er	-	6.5	2.47	4	3.3	2.8
Eu	-	0.2	1.06	1.2	1.3	1.2
F	270	800	800	270	660	625
Fe	47,000	42,000	50,000	51,000	46,500	56,300
Ga	$x.10^{-5}$	1	15	15	19	15
Gd	-	7.5	6.36	10	8	5.4
Ge	$x.10^{-5}$	4	7	7	1.4	1.5
H	8,800	10,000	-	1,500	-	-
He	-	0.01	-	-	-	-
Hf	30	4	4.5	3.2	1	3
Hg	0.X	0.05	0.5	0.07	0.083	0.08
Ho	-	1	1.15	1.3	1.7	1.2
I	0.X	10	0.3	0.5	0.4	0.5
In	$x.10^{-5}$	0.1	0.1	0.1	0.25	0.1
Ir	$x.10^{-4}$	0.01	0.001	0.001	-	-
K	24,000	23,500	25,900	26,000	25,000	20,900
Kr	-	2.10^{-4}	-	-	-	-
La	-	6.5	18.3	18	29	30
Li	40	50	65	65	32	20
Lu	-	1.7	0.75	1	0.8	0.50
Mg	19,400	23,500	20,900	21,000	18,700	23,300
Mn	800	1,000	1,000	900	1,000	950
Mo	X	10	2.3	3	1.1	1.5

Symbol	CLARKE & WASHINGTON (1924)	FERSMAN (1933 to 1939)	GOLDSCHMIDT (1937)	VINOGRADOV (1949)	VINOGRADOV (1962)	TAYLOR (1964)
N	300	400	-	100	19	20
Na	26,400	24,000	28,300	26,400	25,000	23,600
Nb	-	0.32	20	10	20	20
Nd	-	17	23.9	25	37	28
Ne	-	0.005	-	-	-	-
Ni	180	200	100	80	58	75
O	495,200	491,300	466,000	470,000	470,000	464,000
Os	$x.10^{-4}$	0.05	-	0.05	-	-
P	1,200	1,200	1,200	800	930	1,050
Pa	-	7.10^{-7}	-	10^{-6}	-	-
Pb	20	16	16	16	16	12.5
Pd	$x.10^{-5}$	0.05	0.010	$0.01.10^{-10}$	0.013	-
Po	-	0.05	-	2.10^{-10}	-	-
Pr	-	4.5	5.53	7	9	8.2
Pt	0.00X	0.2	0.005	0.005	-	-
Ra	$x.10^{-6}$	2.10^{-6}	-	10^{-6}	-	-
Rb	X	80	280	300	150	90
Re	-	0.001	0.001	0.001	7.10^{-4}	-
Rh	$x.10^{-5}$	0.01	0.001	0.001	-	-
Rn	-	?	-	7.10^{-12}	-	-
Ru	$x.10^{-5}$	0.05	-	0.005	-	-
S	480	1,000	520	500	470	260
Sb	0.X	0.5	(1)	0.4	0.5	0.2
Sc	0.X	6	5	6	10	22
Se	0.0X	0.8	0.09	0.6	0.05	0.05
Si	257,500	260,000	277,200	276,000	295,000	281,500
Sm	-	7	6.47	7	8	6.0
Sn	X	80	40	40	2.5	2
Sr	170	350	150	400	340	375
Ta	-	0.24	2.1	2	2.5	2
Tb	-	1	0.91	1.5	4.3	0.9
Tc	-	0.001	-	-	-	-
Te	0.00X	0.01	(0.001)	0.01	0.001	-
Th	20	10	11.5	8	13	9.6
Ti	5,800	6,100	4,400	6,000	4,500	5,700
Tl	$x.10^{-4}$	0.1	0.3	3	1	0.45
Tm	-	1	0.20	0.8	0.27	0.48
U	80	4	4	3	2.5	2.7
V	160	200	150	150	90	135
W	50	70	1	1	1.3	1.5
Xe	-	3.10^{-5}	-	-	-	-
Y	-	50	28.1	28	29	33
Yb	-	8	2.66	3	0.33	3.0
Zn	40	200	80	50	83	70
Zr	230	250	220	200	170	165

Table 93

The Average Amounts of the Elements in Crustal Rocks in Parts Per Million

(omitting the rare gases and the short-lived radioactive elements)

Atomic Number	Element	Crustal Average	Granite	Diabase
1	H	1,400	400	600
3	Li	20	24	12
4	Be	2.8	3	0.8
5	B	10	2	17
6	C	200	200	100
7	N	20	8	14
8	O	466,000	485,000	449,000
9	F	625	700	250
11	Na	28,300	24,600	15,400
12	Mg	20,900	2,400	39,900
13	Al	81,300	74,300	78,600
14	Si	277,200	339,600	246,100
15	P	1,050	390	650
16	S	260	175	135
17	Cl	130	50	
19	K	25,900	45,100	5,300
20	Ca	36,300	9,900	78,300
21	Sc	22	3	34
22	Ti	4,400	1,500	6,400
23	V	135	16	240
24	Cr	100	22	120
25	Mn	950	230	1,320
26	Fe	50,000	13,700	77,600
27	Co	25	2.4	50
28	Ni	75	2	78
29	Cu	55	13	110
30	Zn	70	45	82
31	Ga	15	18	16
32	Ge	1.5	1.0	1.6
33	As	1.8	0.8	2.2
34	Se	0.05		
35	Br	2.5	0.5	0.5
37	Rb	90	220	22
38	Sr	375	250	180
39	Y	33	13	25
40	Zr	165	210	100
41	Nb	20	20	10
42	Mo	1.5	7	0.05
44	Ru	0.01		
45	Rh	0.005		
46	Pd	0.01	0.01	0.02
47	Ag	0.07	0.04	0.06

Atomic Number	Element	Crustal Average	Granite	Diabase
48	Cd	0.2	0.06	0.3
49	In	0.1	0.03	0.08
50	Sn	2	4	3
51	Sb	0.2	0.4	1.1
52	Te	0.01		
53	I	0.5		
55	Cs	3	1.5	1.1
56	Ba	425	1,220	180
57	La	30	120	30
58	Ce	60	230	30
59	Pr	8.2	20	2
60	Nd	28	55	15
62	Sm	6.0	11	5
63	Eu	1.2	1.0	1.1
64	Gd	5.4	5	4
65	Tb	0.9	1.1	0.6
66	Dy	3.0	2	4
67	Ho	1.2	0.5	1.3
68	Er	2.8	2	3
69	Tm	0.5	0.2	0.3
70	Yb	3.4	1	3
71	Lu	0.5	0.1	0.3
72	Hf	3	5.2	1.5
73	Ta	2	1.6	0.7
74	W	1.5	0.4	0.45
75	Re	0.001	0.0006	0.0004
76	Os	0.005	0.0001	0.0004
77	Ir	0.001	0.006	
78	Pt	0.01	0.008	0.009
79	Au	0.004	0.002	0.005
80	Hg	0.08	0.2	0.2
81	Tl	0.5	1.3	0.13
82	Pb	13	49	8
83	Bi	0.2	0.1	0.2
90	Th	7.2	52	2.4
92	U	1.8	3.7	0.52

(B) COMMONLY OCCURRING ROCKS

Table 95. Average Abundance of Chemical Elements (ppm) in the main types of Igneous and Sedimentary Rocks of the Lithosphere (T. and W.: from TUREKIAN and WEDEPOHL, 1961; V.: from VINOGRADOV, 1962)

Magmatites

Symbol	Ultrabasic Rocks		Basic Rocks (Basalts)		Intermediate Rocks (Syenites) (Diorites)		Acid Rocks (High Ca)	(Low Ca)	Granites etc.
	T. and W.	V.	T. and W.	V.	T. & W.	V.	T. & W.	T.& W.	V.
Ag	0.06	0.05	0.11	0.1	0.0X	0.07	0.051	0.037	0.05
Al	20,000	4,500	78,000	87,600	88,000	88,500	82,000	72,000	77,000
As	1	0.5	2	2	1.4	2.4	1.9	1.5	1.5
Au	0.006	0.005	0.004	0.004	0.00X	-	0.004	0.004	0.004
B	3	1	5	5	9	15	9	10	15
Ba	0.4	1	330	300	1,600	650	420	840	830
Be	0.X	0.2	1	0.4	1	1.8	2	3	5.5
Bi	?	0.001	0.007	0.007	?	0.01	?	0.01	0.01
Br	1	0.5	3.6	3	2.7	4.5	4.5	1.3	1.7
Ca	25,000	7,000	76,000	67,200	18,000	46,500	25,300	5,100	15,800
Cd	0.X	0.05	0.22	0.19	0.13	-	0.13	0.13	0.1
Ce	0.X	-	48	4.5	161	-	81	92	100
Cl	85	50	60	50	520	100	130	200	240
Co	150	200	48	45	1	10	7	1.0	5
Cr	1,600	2,000	170	200	2	50	22	4.1	25
Cs	0.X	0.1	1.1	1	0.6	-	2	4	5
Cu	10	20	87	100	5	35	30	10	20
Er	0.X	-	2.1	2	7.0	-	3.5	4.0	4
Eu	0.X	0.01	0.8	1	2.8	-	1.4	1.6	1.5
F	100	100	400	370	1,200	500	520	850	800
Fe	94,300	98,500	86,500	85,600	36,700	58,500	29,600	14,200	27,000
Ga	1.5	1.5	17	18	30	20	17	17	20
Gd	0.X	-	5.3	5	18	-	8.8	10	9
Ge	1.5	1	1.3	1.5	1	1.5	1.3	1.3	1.4
Hf	0.6	0.1	2.0	1	11	1	2.3	3.9	1

Magmatites continued

Symbol	Ultrabasic Rocks		Basic Rocks (Basalts)		Intermediate Rocks (Syenites)	(Diorites)	Acid Rocks (High Ca)	(Low Ca)	Granites, etc.
	T. & W	V.	T. & W.	V.	T. & W.	V.	T. & W.	T. & W.	V.
Hg	0.0X	0.01	0.09	0.09	0.0X	-	0.08	0.08	0.08
Ho	0.X	-	1.1	1	3.5	-	1.8	2.0	2
I	0.5	0.01	0.5	0.5	0.5	0.3	0.5	0.5	0.4
In	0.01	0.013	0.22	0.22	0.0X	-	0.0X	0.26	0.26
K	40	300	8,300	8,300	48,000	23,000	25,200	42,000	33,400
La	0.X	-	15	27	70	-	45	55	60
Li	0.X	0.5	17	15	28	20	24	40	40
Lu	0.X	-	0.6	0.6	2.1	-	1.1	1.2	1
Mg	204,000	259,000	46,000	45,000	5,800	21,800	9,400	1,600	5,600
Mn	1,620	1,500	1,500	2,000	850	1,200	540	390	600
Mo	0.3	0.2	1.5	1.4	0.6	0.9	1.0	1.3	1
N	6	6	20	18	30	22	20	20	20
Na	4,200	5,700	18,000	19,400	40,400	30,000	28,400	25,800	27,700
Nb	16	1.0	19	20	35	20.0	20	21	20
Nd	0.X	-	20	20	65	-	33	37	46
Ni	2,000	2,000	130	160	4	55	15	4.5	8
P	220	170	1,100	1,400	800	1,600	920	600	700
Pb	1	0.1	6	8	12	15	15	19	20
Pd	0.12	0.12	0.02	0.019	?	-	0.00X	0.00X	0.01
Pr	0.X	-	4.6	4	15	-	7.7	8.8	12
Rb	0.2	2	30	45	110	100	110	170	200
S	300	100	300	300	300	200	300	300	400
Sb	0.1	0.1	0.2	1.0	0.X	0.2	0.2	0.2	0.26
Sc	15	5	30	24	3	2.5	14	7	3
Se	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Si	205,000	190,000	230,000	240,000	291,000	260,000	314,000	347,000	323,000
Sm	0.X	-	5.3	5	18	-	8.8	10	9
Sn	0.5	0.5	1.5	1.5	X	-	1.5	3	3
Sr	1	10	465	440	200	800	440	100	300
Ta	1.0	0.018	1.1	0.48	2.1	0.7	3.6	4.2	3.5
Tb	0.X	-	8	0.8	2.8	-	1.4	1.6	2.5

Magmatites continued

Symbol	Ultrabasic Rocks		Basic Rocks (Basalts)		Intermediate Rocks (Syenites)	(Diorites)	Acid Rocks (High Ca)	(Low Ca)	Granites, etc.
	T. and W.	V.	T. & W.	V.	T. & W.	V.	T. & W.	T. & W.	V.
Th	0.004	0.005	4	3	13	7	8.5	17	18
Ti	300	300	13,800	9,000	3,500	8,000	3,400	1,200	2,300
Tl	0.06	0.01	0.21	0.2	1.4	0.5	0.72	2.3	1.5
Tm	0.X	-	0.2	0.2	0.6	-	0.3	0.3	0.3
U	0.001	0.003	1	0.5	3.0	1.8	3.0	3.0	3.5
V	40	40	250	200	30	100	88	44	40
W	0.77	0.1	0.7	1	1.3	1	1.3	2.2	1.5
Y	0.X	-	21	20	20	-	35	40	34
Yb	0.X	-	2.1	2	7.0	-	3.5	4.0	4
Zn	50	30	105	130	130	72	60	39	60
Zr	45	30	140	100	500	260	140	175	200

Sedimentites					Deep-sea Sediments	
Symbol	Slates T. and W.	Slates + Clays V.	Sandstone T. and W.	Carbonates T. and W.	Carbonates T. and W.	Clays T. & W.
Ag	0.07	0.1	0.0X	0.0X	0.0X	0.11
Al	80,000	104,500	25,000	4,200	20,000	84,000
As	13	6.6	1	1	1	13
Au	0.00X	0.001	0.00X	0.00X	0.00X	0.00X
B	100	100	35	20	55	230
Ba	580	800	X0	10	190	2,300
Be	3	3	0.X	0.X	0.X	2.6
Br	4	6	1	6.2	70	70
Ca	22,100	25,300	39,100	302,300	312,400	29,000
Cd	0.3	0.3	0.0X	0.035	0.0X	0.42
Ce	59	50	92	11.5	35	345
Cl	180	160	10	150	21,000	21,000
Co	19	20	0.3	0.1	0.7	74
Cr	90	100	35	11	11	90
Cs	5	12	0.X	0.X	0.4X	6
Cu	45	57	X	4	30	250
Er	2.5	2.5	4.0	0.5	1.5	15
Eu	1.0	1	1.6	0.2	1.6	6
F	740	500	270	330	540	1,300
Fe	47,200	33,300	9,800	3,800	9,000	65,000
Ga	19	30	12	4	13	20
Gd	6.4	6.5	10	1.3	3.8	38
Ge	1.6	2	0.8	0.2	0.2	2
Hf	2.8	6	3.9	0.3	0.41	4.1
Hg	0.4	0.4	0.03	0.04	0.0X	0.X
Ho	1.2	1	2.0	0.3	0.8	7.5
I	2.2	1	1.7	1.2	0.05	0.05
In	0.1	0.05	0.0X	0.0X	0.0X	0.08
K	26,000	22,800	10,700	2,700	2,900	25,000
La	92	40	30	X	10	115
Bi	?	0.1	?	?	?	?

Sedimentites continued

Symbol	Slates T. & W.	Slates + Clays V.	Sandstone T. & W.	Carbonates T. & W.	Deep-sea Sediments Carbonates T. & W.	Clays T. & W.
Li	66	60	15	5	5	57
Lu	0.7	0.7	1.2	0.2	0.5	4.5
Mg	15,000	13,400	7,000	47,000	4,000	21,000
Mn	850	670	X0	1,100	1,000	6,700
Mo	2.6	2	0.2	0.4	3	27
N	?	600	?	?	?	?
Na	9,600	6,600	3,300	400	20,000	40,000
Nb	11	20	0.0X	0.3	4.6	14
Nd	24	23	37	4.7	14	140
Ni	68	95	2	20	30	225
P	700	770	170	400	350	1,500
Pb	20	20	7	9	9	80
Pd	?	-	?	?	?	?
Pr	5.6	5	8.8	1.1	3.3	33
Rb	140	200	60	3	10	110
S	2,400	3,000	240	1,200	1,300	1,300
Sb	1.5	2	0.0X	0.2	0.15	1.0
Sc	13	10	1	1	2	19
Si	73,000	238,000	368,000	24,000	32,000	250,000
Sm	6.4	6.5	10	1.3	3.8	38
Sn	6	10	0.X	0.X	0.X	1.5
Sr	300	450	20	610	2,000	180
Ta	0.8	3.5	0.0X	0.0X	0.0X	0.0X
Tb	1.0	0.9	1.6	0.2	0.6	6
Th	12	11	1.7	1.7	X	7
Ti	4,600	4,500	1,500	400	770	4,600
Tl	1.4	1	0.82	0.0X	0.16	0.8
Tm	0.2	0.25	0.3	0.04	0.1	1.2
Se	0.6	0.6	0.05	0.08	0.17	0.17

Sedimentites continued					Deep-sea Sediments	
Symbol	Slates T. & W.	Slates + Clays V.	Sandstone T. and W.	Carbonates T. and W.	Carbonates T. and W.	Clays T.& W.
U	3.7	3.2	0.45	2.2	0.X	1.3
V	130	130	20	20	20	120
W	1.8	2	1.6	0.6	0.X	X
Y	26	30	40	30	42	90
Yb	2.6	3	4.0	0.5	1.5	15
Zn	95	80	15	20	35	165
Zr	160	200	220	19	20	150

Table 96. Ratios of Geochemically Important Pairs of Elements (from VINOGRADOV, 1962)

Ratios of Elements	Stony Meteorites (Chondrites)	Ultrabasic Rocks (Dunites)	Basic Rocks (Basalts, Gabbro)	Intermediate Rocks (Andesites, Diorites)	Acid Rocks (Granites, Granodiorites)	Sedimentary Rocks (Clays, Slates)	Mean Composition of the Earth's Crust (2 parts Granite + 1 part basalt)
Al/Ga	4,333	2,250	4,866	4,425	3,850	3,483	4,235
K/Rb	170	150	184	230	167	114	163
Ca/Sr	1,400	700	153	58	53	56	87
Ni/Co	17	70	3.6	5.5	1.6	4.7	3.2
Nb/Ta	15	55	41	26	6	6	8
Mo/W	4	2	1.4	0.9	0.7	1.0	0.8
Zn/Cd	500	600	700	-	600	300	638
Rb/Tl	5,000	200	225	500	133	200	150
Th/U	2.7	1.7	6.0	5.0	5.1	3.4	5.2

Table 101. Examples of the Chemical Composition of the Most Important Igneous Rocks (in mass-% from TROGER, 1930)

A. Intrusive Rocks

	Alkali-granite	Aplite-granite	Grano-diorite	Quartz diorite	Ortho-clase syenite	Soda-syenite	Syenite	Diorite	Gabbro	Dunite	Foyaite	Essexite	Ijolite
SiO_2	75.22	75.70	63.85	64.07	62.03	60.00	58.70	56.06	48.61	38.82	55.22	46.99	43.70
TiO_2	0.13	0.09	0.58	0.45	0.53	0.42	0.95	0.60	0.17	0.00	0.59	2.92	0.89
Al_2O_3	9.93	13.17	15.84	15.82	16.39	16.88	17.09	17.61	17.83	2.24	22.59	17.94	19.77
Fe_2O_3	2.31	0.43	1.91	3.40	0.72	1.83	3.17	1.65	2.08	3.04	1.14	2.56	3.35
FeO	2.19	0.74	2.75	1.44	0.86	3.02	2.29	7.59	5.23	4.90	1.17	7.56	3.47
MnO	0.17	n.d.	0.07	tr.	n.d.	0.12	n.d.	0.16	n.d.	0.28	0.13	tr.	tr.
MgO	0.09	0.15	2.07	3.39	1.60	1.40	2.41	3.38	8.23	44.28	0.28	3.22	3.94
CaO	1.08	0.92	4.76	4.43	3.60	3.16	4.71	7.26	13.72	0.00	2.12	7.85	10.30
Na_2O	4.78	3.59	3.29	4.06	1.08	9.31	4.38	3.47	2.63	0.20	8.76	6.35	9.78
K_2O	4.06	4.77	3.08	2.27	12.38	0.94	4.35	1.67	0.32	n.d.	5.59	2.62	2.87
H_2O+	0.31	0.68	1.65	0.42	0.61	1.53	0.89	0.95	0.99	5.68	1.77	0.65	0.89
H_2O-	-	-	0.28	0.10	0.24	0.43	0.23	-	-	-	0.39	-	-
P_2O_5	n.d.	tr.	0.13	0.18	0.13	0.14	0.23	n.d.	0.08	n.d.	0.00	0.94	1.34
CO_2	-	-	-	-	-	0.59	0.00	-	0.00	0.60	-	-	-
BaO	-	-	0.06	-	-	0.06	-	-	-	-	-	0.00	-
SrO	-	-	tr.	-	-	0.02	-	-	-	-	-	-	-
others	-	-	0.04	0.05	-	0.03	-	-	0.05	0.28	0.52	-	-
Sum	100.27	100.24	100.36	100.08	100.17	99.88	99.40	100.40	99.94	100.32	100.27	99.00	100.30

B. Extrusive Rocks

	Quartz kerato-phyre	Pan-telle-lerite	Quartz por-phyry	Rhyo-lite	Plagio-phyre	Rhyo-dacite	Quartz por-phyrite	Dacite	Ker-ato-phyre	Soda-tra-chyte	Ortho-phyre	Trachyte
SiO_2	67.90	69.79	76.03	74.02	64.54	67.16	63.39	66.76	61.67	62.91	63.24	61.25
TiO_2	0.24	0.89	n.d.	0.02	1.09	0.87	0.44	1.02	0.34	0.94	tr.	0.05
Al_2O_3	14.36	11.91	11.76	13.20	15.83	14.86	16.58	14.41	17.47	18.25	16.83	17.70
Fe_2O_3	4.36	5.35	1.99	0.75	1.75	0.43	1.41	2.74	1.37	2.08	4.86	2.95
FeO	1.44	1.43	n.d.	0.29	2.80	3.87	3.08	2.23	3.92	1.47	0.07	1.40
MnO	0.32	0.20	n.d.	tr.	0.26	0.07	tr.	n.d.	tr.	n.d.	tr.	n.d.
MgO	0.22	0.25	0.27	0.06	1.01	1.61	2.15	2.01	2.13	0.20	0.57	0.07
CaO	1.34	0.25	0.45	0.56	2.13	2.84	4.76	3.64	0.18	0.87	0.72	3.10
Na_2O	6.89	5.66	3.36	4.18	5.25	2.48	3.47	3.02	8.52	6.87	4.02	3.40
K_2O	1.85	4.59	5.61	4.82	2.95	3.77	2.79	2.51	3.38	5.85	7.37	8.08
H_2O^+	1.52	0.17	0.63	1.86	1.39	0.90	1.87	0.62	0.45	0.47	1.13	1.35
H_2O^-	-	0.04	-	-	0.42	0.12	0.22	0.77	-	-	-	-
P_2O_5	n.d.	0.13	n.d.	n.d.	0.00	0.53	0.14	0.39	0.06	0.19	0.16	1.10
CO_2	-	-	-	-	0.27	0.20	-	-	0.05	-	0.00	-
BaO	-	-	-	-	0.06	-	0.11	-	-	-	-	-
others	tr.	-	-	tr.	0.15	0.02	-	-	-	-	0.43	-
Sum	100.44	100.66	100.10	99.76	99.91	99.74	100.41	100.12	99.54	100.10	99.40	100.45

	Porphyrite	Andesite	Diabase	Basalt	Sideromelane	Palagonite	Phonolite	Leucite phonolite	Nephelinite phrite	Leucite-tephrite	Nephelinite	Olivine Leucitite	Picrite
SiO_2	54. 94	57.35	50.20	50.32	51.90	33.00	56.56	55.87	46.26	48.74	40.99	42.20	40.02
TiO_2	1.11	0.64	1.21	3.10	1.60	2.30	0.23	0.79	1.69	1.04	2.41	2.44	0.59
Al_2O_3	18.38	17.54	16.08	12.83	14.70	8.30	21.31	20.85	18.98	16.38	16.50	12.13	8.32
Fe_2O_3	3.15	3.33	9.30	1.74	1.60	15.20	1.03	2.34	7.39	1.64	10.62	7.27	1.51
FeO	3.02	3.87	3.87	9.93	8.60	-	1.79	1.10	3.27	5.30	n.d.	4.62	11.14
MnO	n.d.	tr.	0.54	0.10	tr.	0.10	0.11	n.d.	n.d.	0.14	0.35	n.d.	0.85
MgO	3.59	4.29	6.82	7.39	8.70	5.00	0.15	0.48	3.09	7.07	3.29	9.24	27.63
CaO	6.29	6.91	7.85	11.06	10.40	7.00	1.24	3.07	10.59	12.19	12.63	14.32	4.04
Na_2O	3.97	4.01	2.34	2.38	2.60	0.70	9.47	4.81	5.51	2.01	5.95	2.75	0.65
K_2O	2.31	2.54	1.24	0.41	0.40	0.30	5.25	10.49	1.99	4.95	2.36	3.69	0.32
H_2O+	2.39	0.79	0.67	0.33	0.20	9.30	0.25	0.34	0.96	0.55	2.63	0.66	4.30
H_2O^-	-	-	-	0.05	0.16	18.30	1.70	-	-	0.16	-	-	0.70
P_2O_5	0.27	0.08	n.d.	0.30	-	-	0.06	0.11	0.49	0.18	0.89	0.80	n.d.
CO_2	0.69	-	-	-	-	-	0.24	0.00	-	-	-	-	-
BaO	-	-	-	-	-	-	-	0.09	-	-	-	-	-
others	0.12	0.03	-	0.04	-	-	0.61	0.21	-	0.07	1.00	0.04	0.51
Sum	100.23	101.38	100.12	99.98	100.86	99.50	100.00	100.55	100.22	100.42	99.62	100.16	100.58

Table 102. Average Concentrations of Elements in Granitoid Rocks in Saxony and Thuringia (BRAUER, 1965) n.d. = not detectable

Granite Massif	Element Concentrations (ppm)															No. of Test Samples
	Sn	Li	Be	Ti	Cr	V	Co	Ni	Mn	Ba	Sr	La	Y	Pb	Cu	U	
A. Saxony																	
Zinnwald (greisen)	62	8,250	41	94	<1	<5	-	-	975	50	8	10	<10	5	1.0	12	4
Markersbach granite	5	300	4.0	90	1	-	-	<1	85	50	5	10	10	30	3.0	6	1
Altenberg granite	205	1,200	1.1	15	<1	-	-	<1	150	10	8	<10	-	14	2.5	32	2
Schellehau granite	86	830	10	277	2	5	-	<1	83	150	51	10	13	32	3.0	12	4
Bobritzsch granite	10	220	<1	1,950	43	38	7	13	147	1,000	458	77	167	22	21	5	12
Granite from Geyer	37	813	1.6	136	<1	-	-	<1	98	47	10	13	<10	-	2.1	12	6
Granite from Ehrenfriedersdorf	120	1,468	1.3	87	<1	-	-	<1	78	30	69	<10	<10	5	2.2	7	10
Auerhammer granite	10	300	1.0	2,700	3	18	<3	10	84	1,000	300	100	122	8	1.3	8	4
Schwarzenberg granite	13	100	3.7	362	6	<5	-	<1	61	106	73	20	30	10	1.8	5	4
Eibenstock granite (coarse grained)	27	562	2.0	556	<1	<5	-	<1	69	78	42	25	24	8	2.4	7	20
Eibenstock granite (medium grained)	23	600	3.6	398	1	<5	-	<1	72	43	12	15	16	<5	2.4	6	8
Eibenstock granite (fine grained)	45	603	2.4	338	<1	<5		<1	49	28	11	15	12	6	2.7	11	14
Kirchberg granite (medium grained)	10	272	1.1	1,528	7	19	<3	<1	135	400	540	26	91	36	7.3	8	5
Kirchberg granite (small grained)	10	280	1.3	1,300	18	13	<3	<1	101	475	378	25	66	22	2.7	9	4
Kirchberg granite (fine grained)	10	195	3.6	425	<1	<5	<3	<1	52	67	36	11	18	25	4.7	12	5
Bergen granite (coarse grained)	13	373	2.4	756	1	7	<3	<1	138	234	75	53	33	13	3.0	11	3
B. Thuringia																	
Sparnberg granite	26	100	1.7	82	<1	<5	-	<1	92	75	8	10	10	10	1.8	4	2
Granite from Henneberg	24	152	4.0	1,725	11	19	3	<1	66	625	600	20	71	33	1.0	7	4
Granite from Sormitztal	45	100	1	1,600	25	30	7	10	107	300	300	30	120	40	9.5	4	2
Schleusetal granite	<10	<100	-	213	<1	<5	-	<1	20	75	18	10	<10	7	1.0	1	3
Suhl granite	<10	110	-	2,914	61	120	14	21	75	568	390	192	197	15	12	4	45

Granite Massif	Element Concentrations (ppm)														No. of U Test Samples	
	Sn	Li	Be	Ti	Cr	V	Co	Ni	Mn	Ba	Sr	La	Y	Pb	Cu		
Diorite from Brotterode	<10	133	-	5,000	300	233	50	>300	n.d.	692	450	233	757	5	7.5	4	3
Ruhla granite	<10	103	-	2,440	47	56	8	37	78	776	348	55	142	9	6.4	2	25

Table 110. Chemical Composition of a Few Metamorphic Rock-types (from CORRENS, 1950; data in mass-%)

	Leptite	Noritic Granulite	Biotite Gneiss	Amphibolite	Eclogite	Andradite Skarn	Disthene Quartzite	Quartz-Muscovite Chlor. Phyllite	Hornblende (Glaucophane) Schist	Chlorite Schist with Epidote
SiO_2	78.02	52.03	67.46	49.73	46.26	42.84	89.38	58.32	47.54	49.22
TiO_2	0.11	2.27	0.47	0.56	0.28	0.35	0.16	0.98	1.24	0.18
Al_2O_3	12.22	16.39	15.81	16.05	14.45	4.56	6.57	20.00	19.22	18.56
Fe_2O_3	0.61	0.82	0.17	2.44	4.41	10.60	1.56	2.01	4.58	2.22
FeO	0.86	9.13	3.63	7.96	5.82	8.94	0.50	4.98	2.98	5.35
MnO	0.01	0.17	tr.	0.20	n.d.	0.63	0.01	0.22	0.06	0.12
MgO	tr.	7.04	2.35	7.84	11.99	4.03	0.00	1.85	5.36	8.15
CaO	0.41	8.78	2.97	10.22	11.66	26.24	0.06	0.66	7.90	7.17
Na_2O	4.28	2.14	3.18	2.99	2.45	0.00	0.05	1.26	3.63	4.65
K_2O	3.16	1.21	2.08	0.61	1.51	0.12	0.51	4.49	1.89	0.10
H_2O	0.48	0.35	1.28	1.03	1.10	0.78	1.18	4.05	6.00	3.15
others	-	0.23	0.27	0.12	-	1.00	0.14	1.15	0.05	0.45
Sum	100.16	100.56	99.67	99.75	99.93	100.09	100.12	99.97	100.45	99.32

(C) SOILS

Table 117. Mean Contents of Chemical Elements in Soil Compared with the Contents in the Lithosphere; compiled from VINOGRADOV (1954, soil) and (1962, lithosphere)

Element	Lithosphere	Soil
O	47.0 mass-%	49.0 mass-%
Si	29.5	33.0
Al	8.05	7.13
Fe	4.65	3.8
Ca	2.96	1.37
Na	2.5	0.63
K	2.5	1.36
Mg	1.87	0.6
Ti	4,500 ppm	4,600 ppm
Mn	1,000	850
P	930	800
F	660	200
Ba	650	500
S	470	850
Sr	340	300
C	230	20,000
Cl	170	100
Zr	170	300
Rb	150	60
V	90	100
Cr	83	200
Zn	83	50
Ce	70	(50)
Ni	58	40
Cu	47	20
Li	32	30
Ga	19	(X·10)
N	19	1,000
Co	18	8
Pb	16	10
Th	13	6
B	12	10
Be	3.8	X
Cs	3.7	(5)
Sn	2.5	(X·10)
U	2.5	1
As	1.7	5
Ge	1.4	X
Mo	1.1	3
I	0.4	5
Cd	0.13	(0.5)
Hg	0.083	0.0X
Se	0.05	0.01_{-7}
Ra	1.10^{-6}	8.10^{-7}

SECTION B

STABILITY CONCEPTS INVOLVING MINERAL TAILINGS

Stability is a relative property. For example, calcite is said to be stable at ordinary temperatures and pressures. So it is, but only in the sense that under specific conditions it remains unchanged indefinitely. Drop it into dilute hydrochloric acid, however, and it is certainly far from stable. Stability must therefore be defined not only in respect to pressure and temperature, but also with regards to chemical environment. Strictly speaking, one cannot discuss the stability of a single phase (mineral) in a rock independent of the associated minerals and the pore fluids. Most discussions of particular minerals or mineral associations assume an indifferent chemical environment in which stability is a function of physical conditions only.

The decomposition of sulphides in a tailings area frequently creates chemical conditions that adversely affect the stability of many of the non-sulphide mineral species that are present. Although these non-sulphide minerals are, in general, characterized by their relative stability in a natural environment, they do break down very slowly and release anions and cations that help to make up natural background concentrations. In a tailings basin, the enormous overall surface area of the tailings mass itself is such that the slow breakdown of the various non-sulphide minerals becomes significant since the soluble reaction products frequently end up in a concentrated form in the seepage or decant overflow from the area. A few grams of tailings taken from almost any disposal area will contain at least traces of most of the elements known to man. It is for this reason that strict attention must be paid to the type and reactivity of all rocks and minerals that occur in or are associated with an orebody.

The natural background chemical concentrations found in watersheds in mining areas are a result of the natural solubilization of the earth's crust in these areas. If the crust in these areas contains relatively abnormal concentrations of various elements, the elements may be expected to occur in abnormal concentrations in the natural waters of the area. It is interesting to note that many minor elements become trapped or occur in the minerals that form the rocks in any specific location. The chemical-physical decomposition of these rocks (in situ or in a tailings mass) may force the minor elements into solution and hence into area watercourses.

THE CHEMICAL DECOMPOSITION OF SILICATES

Silicate materials and quartz generally represent the bulk of discarded material in a tailings area that serves a mining operation. From a relative standpoint, quartz and the silicates must be regarded as some of the more stable components of the earth's crust. However, under no circumstances should quartz and especially the silicates be regarded as chemically inert.

ANY SOLUTION IN CONTACT WITH SILICATE MINERALS WILL TEND TO BECOME ALKALINE. How alkaline it becomes depends on the nature of the silicates. A restraint on the increase in alkalinity is set by reactions of various forms of silica with OH^-:

$$H_2O + SiO_2 \text{ (quartz)} + OH^- \text{ -----} > H_3SiO_4^- \quad K = 10^{0.4}$$

$$H_4SiO_4 \text{ (aq.)} + OH^- \text{ -----} > H_3SiO_4^- + H_2O \quad K = 10^{4.2}$$

These processes ordinarily keep the pH from rising much above 9.

The weathering of silicates is primarily a process of hydrolysis. As a simple example, the mineral forsterite (magnesium-rich olivine) hydrolyzes according to the equation

$$Mg_2SiO_4 + 4H_2O \text{ -----} > 2Mg^{++} + 4OH^- + H_4SiO_4$$

the hydrogen ion from water uniting with the silicate group to form the very weak silicic acid. Surface waters generally contain a little more H^+ than would be present in pure water, because of their dissolved CO_2, and this additional H^+ aids the process of hydrolysis. The carbonic acid may be included in the equation:

$$Mg_2SiO_4 + 4H_2CO_3 \text{ -----} > 2Mg^{++} + 4HCO_3^- + H_4SiO_4$$

When acids that are stronger than carbonic are present, as in the case of an acid mine drainage situation, the reaction becomes simply

$$Mg_2SiO_4 + 4H^+ \text{ -----} > 2Mg^{++} + H_4SiO_4$$

As such, the equation for hydrolysis may be written in various ways depending on the local availability of hydrogen ion. These reactions are almost exactly analogous to reactions that might be written for carbonates:

$$MgCO_3 + H_2O \text{ -----} Mg^{++} + OH^- + HCO_3^-$$

$$MgCO_3 + H_2CO_3 \text{ -----} Mg^{++} + HCO_3^- + HCO_3^-$$

$$MgCO_3 + 2H^+ \text{ -----} \rightarrow Mg^{++} + H_2CO_3$$

The only significant difference is that the weak acid formed in the first two equations consists of ions (HCO_3^-) rather than neutral molecules (H_4SiO_4) which reflects the fact that carbonic acid is stronger than silicic acid. Neither the carbonate nor the silicate reactions are strictly reversible for at ordinary temperatures the addition of Mg^{++} to a bicarbonate or silicic acid solution gives hydrated compounds rather than the anhydrous salts.

For silicates containing several cations the hydrolysis reaction is less simple than for forsterite because in general the different cations go into solution at different rates. At any stage of partial weathering, silicate grains are coated with an outer shell from which some cations have been preferentially removed, hence which must have a different composition from the mineral as a whole. This outer shell serves to "armor" the interior of a grain and makes the dissolving of most silicates extremely slow.

Aluminum silicates involve the further complication that one product of their weathering is practically always a clay mineral, a compound in which some of the original aluminum and silicon apparently remain combined. The reaction can be symbolized by using K-feldspar as an example of an aluminum silicate and kaolinite as a clay mineral:

$$4KAlSi_3O_8 + 22H_2O \text{ -----} \rightarrow 4K^+ + 4OH^- + Al_4Si_4O_{10}(OH)_8 + 8H_4SiO_4$$

In summary, the weathering of silicates is chiefly a hydrolysis reaction, making the weathering solution alkaline or at least reducing its acidity and yielding as principal products cations and silicic acid in solution and clay minerals as residual solids.

NOTE: The solubility of quartz (SiO_2) in water at 25°C and atmospheric pressure has been stated to be between .54 ppm and 11 ppm.

THE pH PRODUCED BY MINERAL PARTICLES IN CONTACT WITH WATER

The acidity-alkalinity of an aqueous solution is conveniently expressed by the designation, "pH", a number taken originally from the reciprocal of the effective hydrogen ion concentration. At neutrality, pH 7, the effective concentration of H^+ and OH^- ions are both 10^{-7} mols per liter. As the pH becomes less (numbers below 7), the effective H^+ ion concentration becomes greater and the solution becomes more acid. At pH values higher than 7, the effective concentration of H^+ ions becomes less and the effective concentration of OH^- ions is greater, whereby the aqueous solution is alkaline.

Quartz (SiO_2) pulverized in water hydrolyzes to a pH about 6 to 7 which is slightly acid to neutral; the feldspars hydrolyze to produce pH 8 to 10; the amphiboles and feldspathoids 10 to 11. This range in pH values is exceedingly important because of its effect on the relative solubilities of Al_2O_3 and SiO_2 which are also products of the hydrolysis reaction.

At pH 10 and higher, both Al_2O_3 and SiO_2 are relatively soluble and therefore the small amounts of them that are released during hydrolysis at these high pH values are likely to be carried away in solution.

For example, the Al_2O_3 and SiO_2 released from hydrolyzing nepheline and from amphiboles (pH 10-11) are likely to be carried away, unless or until their solutions meet with conditions which either (1) reduce the pH, or (2) evaporate part of the water.

Assume that the pH of a solution derived from hydrolyzing nepheline is reduced from pH 10 to pH 8 (which is quite probable in nature), and observe the effect on the solubility of Al_2O_3 and SiO_2. pH 8 the solubility of Al_2O_3 is reduced to almost nil, but the solubility of SiO_2 is reduced only about one-fourth of what it is at pH 10. It is expected, therefore, that at pH 8 hydrated Al_2O_3 will be precipitated, probably as gibbsite ($Al_2O_3.3H_2O$) or as diaspore or boehmite ($Al_2O_3.H_2O$) the common minerals in bauxite, whereas most or all of the SiO_2 will remain in solution and be carried away.

Mineral Name	pH when pulverized in water
Amphiboles	
Actinolite	11
Hornblende	10
Carbonates	
Calcite	8
Dolomite	9, 10
Siderite	5, 6, 7
Clay Minerals and Al Oxides	
Kaolinite	5, 6, 7
Montmorillonite	6, 7
Boehmite	6, 7
Diaspore	6, 7
Gibbsite	6, 7
Feldspars	
Albite	9, 10
Oligoclase	9
Labradorite	8, 9
Anorthite	8
Orthoclase	8
Microcline	8, 9
Feldspathoids	
Nepheline	10-11
Leucite	10
Micas	
Biotite	8, 9
Muscovite	7, 8
Olivine	10, 11
Pyroxenes	
Aegirite	9
Augite	10
Diopside	10, 11
Hypersthene	8
Quartz	6, 7

The resistance to weathering of rocks and their constituent minerals varies considerably (so-called weathering series). A survey of the resistance to weathering offered by heavy minerals and a few other important minerals is given in Table 112.

Table 112. (Resistance to Weathering of Some Rock-forming Minerals, Especially Heavy Minerals partly from RUKHIN, 1958)

Non-resistant minerals	Moderately resistant minerals	Resistant minerals	Highly resistant minerals
Olivine	Apatite	Anatase	Limonite
Rhombic pyroxenes	Diopside-	Staurolite	Andalusite
Augite (Fe)	Hedenbergite	Disthene	Topaz
Vesuvianite	Allanite	Ilmenite	Brucite
Ordinary amphibole (Na, Fe)	Ca-Fe garnets	Hematite	Leucoxene
Pyrite and many sulphides	Actinolite	Titanite	Chromspinel
Cinnabar	Tremolite	Titanomagnetite	Rutile
Melanite	Epidote	Magnetite	Tourmaline
Glauconite	Zoisite	Monazite	Gold
Biotite	Wolframite	Xenotime	Platinum
Basic plagioclase	Scheelite	Perovskite	Spinel
Feldspathoids	Ottrelite	Columbite	Zircon
Calcite	Axinite	Cassiterite	Corundum
Dolomite	Baryte	Muscovite	Diamond
Gypsum	Sillimanite	Orthoclase-	Quartz
	Interm. plagioclase	Albite	

Table 113. Relative Mobility of Various Elements in Weathering Processes

	Type of Rock	Main Elements	Trace Elements
1.	Gabbroid Rocks WIEWORA (1967)	Ca Na Mg Si K Al=Fe	Mn Ni Ti Cr V
2.	Porphyrites	Ca Mg Na K Si Al=Fe	Co Mn Ni=Cr=V Cu Zr P=Ti Ga

Table 116. Possibilities of the Formation of Polynuclear Complexes by Hydrolysis (after PACHADZHANOV, 1964)

Cation	Complex $M(A_tM)_n$ *
Be^{2}	$Be(OBe)_4^{2+}$; $Be_n(OH)_n^{n+}$
Al^{3+}	Within the acid range: $Al_6(OH)_{15}^{2+}$
Al^{3+}	Within the alkaline range: $Al(OH)_4^- + Al(OH)_{3t}$
Ga^{3+}	Probably analogous to Al^{3+}
Fe^{3+}	$(Fe_4O_3(OH)_5)^+$; $Fe((OH)_2Fe)_n^{n+3}$
Sc^{3+}	$Sc((OH)_2Sc)_{n+1}^{+(3+n)}$
Ti^{4+}	$Ti\{^{O}_{HTi}\}_n^{+(n+4)}$
Zr^{4+}, Hf^{4+}	$M(OM)_n^{+(n+4)}$
Th^{4+}	$Th((OH)_3Th)_n^{n+4}$
U^{4+}	$U\{^{O}_{OHU}\}_n^{4+n}$
Ce^{4+}	$Ce_6O_4(OH)_4^{12+}$
V^{5+}	$VO_2((OH)_t(VO_2))_n$
Nb^{5+}, Ta^{5+}	$MO_2((OH)_t(MO_2))_n$
U^{6+}	$UO_2\{^{(OH)_2UO_2}_{O}\}_n^{2+}$

* M complex forming agent
A bridge group
t constant
n variable

SECTION C

LEVELS OF SPECIFIC CHEMICAL ELEMENTS IN ONTARIO TAILINGS AREAS WITH BACKGROUND DATA

(1)

Aluminum

(a) Al concentration range in Ontario tailings areas (121 samples) 1,660 - 95,700 ppm

(b) Average Al concentration in Ontario tailings areas (121 samples) - 29,005 ppm

(c) Aluminum Background Data

NOTE: Also see Section A of this report

Abundance

In the earth's crust aluminum is the dominant metal; in the mantle its place is taken by magnesium. The average aluminum content (by weight) of igneous rocks, excluding ultrabasics, is approximately 8%, about one third of the silicon content. The value for the crust as a whole is 81,300 g/t and the estimated value for the whole earth is 0.44% only.

Geochemistry

Aluminum is not only abundant but widespread throughout the crust. This is no doubt partly due to the fact that the aluminum ion can exist, under different circumstances, in both four-fold and six-fold co-ordination. It is therefore able to enter into a great range of silicate structures as well as forming a variety of other oxygen compounds.

There is also an interesting group of fluorine compounds of aluminum. As might be expected for so strongly lithophile an element, aluminum does not form any terrestrial sulphide minerals, nor do they exist in meteorites.

The ionic radius of aluminum is 0.51A for six-fold co-ordination which compares with

0.64 for Fe^{3+}, 0.63 for Cr^{3+}, and 0.41 for Si^{4+}.

In minerals where aluminum is in this co-ordination it is usually possible for replacement to take place, particularly with ferric iron and chromium. For tetrahedral four-fold co-ordination the aluminum functions as the centre of an anionic AlO_4 group and in effect is deputizing for silicon. It is thus possible for aluminum to enter both cationic and anionic structures and both of these may sometimes exist in the same mineral. The following examples may be noted:

Corundum Al_2O_3 \
Spinel $MgAl_2O_4$ / Six-fold co-ordination - Al replaceable by Fe^{3+} or Cr^{3+}

Orthoclase	$KAlSi_3O_8$	Four-fold co-ordination -
Anorthite	$CaAl_2Si_2O_8$	alumino-silicate ion
Kyanite	Al_2SiO_5	Half the Al ions four-fold, half the Al ions six-fold

Undoubtedly the most important rock minerals are the feldspars and they have structures in which up to one half of the tetrahedral positions in the framework are occupied by Al and positive ions are present in sufficient number to neutralize the negative charge of the $(Si, Al)O_2$ framework. As the feldspars are the most abundant of the essential components of igneous rocks (excepting the ultrabasic rocks) it will be understood that by far the largest amount of aluminum in the earth's crust is contained in these minerals.

Two other classes of aluminosilicates should be mentioned, although of less importance than the feldspars. These are the feldspathoids and the zeolites. Both types have the same basic $(SiAl)O_2$ framework as the feldspars but it is more open in structure. The feldspathoids, of which examples are nepheline $NaAlSiO_4$ and leucite $KAlSi_2O_6$, are readily attacked by acids with the removal of the aluminum and the cations, leaving gelatinous silica. They are therefore rather susceptible to weathering processes.

The zeolites are hydrous minerals of very open structure, an example being analcime $NaAlSi_2O_6.H_2O$. They readily lose water when heated and have exchangeable cations. The zeolites are secondary products often found in the cavities of igneous rocks.

In the formation of the crust of the earth it is clear that aluminum is associated with the main crystallization, but a certain amount remains to the later stages so that feldspars, micas, and some other aluminosilicates are often found well crystallized in pegmatite dykes and veins. Aluminum is, however, conspicuous by its paucity or absence in the pneumatolytic and hydrothermal stages. A special aspect of aluminous pegmatitic minerals is the occurrence of cryolite and related alumino-fluorides at Ivigtut in Greenland and at one or two other localities. It would appear that the conditions for the formation of such compounds in nature are rather uncommon.

COMMON ALUMINUM MINERALS

Name		Occurrence
Corundum	Al_2O_3	Metamorphic rocks
Diaspore	$AlOOH$	Hydrolysate sediments
Boehmite	$AlOOH$	
Gibbsite	$Al(OH)_3$	
Spinel	$MgAl_2O_4$	Metamorphic rocks
Fluellite	$3AlF_3 4H_2O$	Volcanic emanations
Cryolite	Na_3AlF_6	Granite pegmatites
Chiolite	$Na_5Al_3F_{14}$	
Elpasolite	K_2NaAlF_6	
Weberite	Na_2MgAlF_7	
Eremeyerite	$AlBO_3$	Hydrothermal veins
Dawsonite	$NaAlCO_3(OH)_2$	
Alumohydrocalcite	$CaAl_2(CO_3)_2(OH)_4 3H_2O$	
Andalusite	Al_2SiO_5	Metamorphic rocks
Kyanite		
Sillimanite		
Mullite	$Al_9Si_3O_{19½}$	
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	
Dickite	$Al_2Si_2O_5(OH)_4$	Clay minerals
Kaolinite		
Nacrite		
Nepheline	$NaAlSiO_4$	Igneous rocks
Albite	$NaAlSi_3O_8$	
Orthoclase	$KAlSi_3O_8$	
Microcline	$KAlSi_3O_8$	
Analcime	$NaAlSi_2O_6 H_2O$	Zeolitic
Muscovite	$KAl_3Si_3O_{10}(OH)_2$	Igneous rocks
Phlogopite	$KMg_3AlSi_3O_{10}(OH)_2$	
Anorthite	$CaAl_2Si_2O_8$	

COMMON ALUMINUM MINERALS continued

Name	Formula	Occurrence
Almandine	$Fe_3^{3+}Al_2Si_3O_{12}$	Metamorphic rocks
Cordierite	$(MgFe^{2+})_2Al_4Si_5O_{18}$	
Topaz	$Al_2SiO_4(OH,F)_2$	Igneous-pneumatolytic weathered rocks
Berlinite	$AlPO_4$	Metamorphic rocks
Variscite	$AlPO_4 2H_2O$	
Wavellite	$Al_6(PO_4)_4(OH)_6 9H_2O$	Metamorphic rocks
Turquoise	$CuAl_6(PO_4)_4(OH)_8 5H_2O$	Altered aluminous rocks
Alunogen	$Al_2(SO_4)_3 18H_2O$	Altered aluminous rocks
Aluminite	$Al_2(SO_4)(OH)_4 7H_2O$	
Alum	$KAl(SO_4)_2 12H_2O$	
Kalinite	$KAl(SO_4)_2 11H_2O$	
Alunite	$KAl_3(SO_4)_2(OH)_6$	

Weathering of Aluminous Minerals

The action of meteoric and hydrothermal waters on the primary minerals of aluminum may take place in several ways. These are indicated below.

(i) The mineral is dissolved, the cations leached out and the aluminum and silicon undergo hydrolysis and re-combination to yield aluminum silicate clay minerals of various kinds. This process gives rise to most of the common clays and under special conditions where granite has been pneumatolysed in depth, a massive china clay rock is formed.

(ii) In tropical and sub-tropical climates of heavy rainfall the rate of weathering of rocks is high and most of the products formed do not remain in situ. Within the pH range 5-9 aluminum and ferric hydroxides are less soluble than silica and consequently deposits of the two basic hydrated oxides are formed, largely free of silica. These are known as laterites and if low in iron may actually be valuable deposits of the mixture of hydrated aluminum oxides called bauxite.

There is a marked differentiation in sedimentation so that arenaceous (sandy) and calcareous (limestone) rocks may be almost free of aluminum whereas the argillaceous rocks (clays, shales, slates) may be relatively rich in the element.

The rather uncommon argillaceous limestones are sometimes altered by weathering so as to remove the calcium carbonate. The residue may then become available as a form of bauxite deposit.

Main Products

Illite	$(H_3O,K)_4Al_8(Si,Al)_{16}O_{40}(OH)_8$
Kaolinite	$Al_2Si_2O_5(OH)_4$
Montmorillonite	approx. $(Al,Mg)_2Si_4O_{10}(OH)_2nH_2O$
Chlorite	$(Mg,Fe,Al)_6Si_4O_{10}(OH)_8$
Vermiculite	$Mg_3Si_4O_{10}(OH)_2nH_2O$

During weathering under temperate conditions, and with good drainage, the more important aluminum-bearing minerals such as feldspars and feldspathoids, give rise to the clay minerals illite, averaging about 13.5% Al, and kaolinite, with almost 21% Al. Illite apparently represents a less advanced stage of weathering and can, in its turn, give rise to kaolinite. Under conditions of poor drainage and with a certain amount of available magnesia and ferrous iron, montmorillonite (usually with about 11% Al) is found in place of illite and kaolinite.

Muscovite is much more resistant to weathering than the feldspars and the feldspathoids, but eventually goes, like them, through illite to kaolinite. Less is known with certainty about the weathering of biotite. In some instances it changes to hydrobiotite and then to vermiculite (7.5% to 9.0% Al). Recently, a tri-octahedral montmorillonoid has been found in certain soil clays, derived from biotite, or possible vermiculite. Hornblende and pyroxene usually weather to chlorite in the first instance, while chlorite may also weather to vermiculite.

The great bulk of the aluminum in the original minerals is contained in the newly formed clay minerals, and only a small amount goes into solution. Analyses of the material in solution in river waters given by Clarke (1924) show that these waters contain from a trace to 4 ppm of Al. But where much organic matter is present it may be supposed that more Al would go into solution. Acid soil solutions, for instance, often contain appreciable aluminum, and this element is leached from the upper horizons of podzols, to be enriched to some extent in the B horizon. Moreover, many Scottish oil clays contain numerous flakes of a trioctahedral clay mica which Walker (1950) believes

to be authigenic and not a residual mineral produced by the alteration of the original biotites of the parent rocks.

Under conditions of extreme weathering, silicon is leached as well as alkalis, and bauxite (or laterite) is formed. The aluminum here is largely in the form of gibbsite (hydrargillite) (34.6% Al) and boehmite or diaspore (both containing some 45% Al) together with colloidal aluminum hydroxides.

(2)

Antimony

(a) Sb concentration range in Ontario tailings areas (121 samples) <10 - 1,590 ppm

(b) Average Sb concentration in Ontario tailings areas (121 samples) - 256 ppm

(c) Antimony Background Data

NOTE: Also see Section A of this report

There are two stable isotopes of antimony in nature:

$$^{121}Sb = 57.25\%$$
$$^{123}Sb = 42.75\%$$

There appears to be no perceptible variation in the isotopic ratio. The relative abundances of antimony under cosmic and terrestrial conditions do not difer significantly.

Geochemistry

Antimony is among the rarer elements in the earth's crust with an abundance of about 0.2g/ton. It is very definitely thiophile in its distribution and as usual with such elements it is often found in concentrations connected with the later phases of igneous activity. Antimony minerals are generally found in low-temperature hydrothermal deposits which may often, as is also the case with mercury, be at a considerable distance from the original magmatic source. The number of antimony minerals, which includes the free element, is not large. Unlike arsenic, it does not readily from stable oxy-salts in the pentavalent state and, unlike bismuth, it is not sufficiently electropositive to form many salts with the common anions.

The amount of antimony involved in the formation of sedimentary rocks is very small and the changes it undergoes are obscure. There is some evidence that it may, like arsenic, be concentrated in hydrolysate material of ferruginous type. The antimony content of sea water is almost beyond the limits of detection, but very small amounts (about 0.2 ppm) have been reported in some marine animals.

About thirty different complex sulpho-salts containing antimony are recorded as minerals in addition to those which follow:

ANTIMONY MINERALS

Name	Formula
Antimony	Sb
Allemontite	AsSb
Allargentum	Ag,Sb
Aurostibite	$AuSb_2$
Famatinite	Cu_3SbS_4
Stibnite	Sb_2S_3
Cylindrite	$Pb_3Sn_4Sb_2S_{14}$
Valentinite	Sb_2O_3
Swedenborgite	$NaBe_4SbO_7$
Nadorite	$PbSbO_2Cl$
Klebelsbergite	Hydrated basic sulphates
Jamesonite	$Pb_4FeSb_6S_{14}$

The radius of the positive antimony ion Sb^{5+} is about 0.62A, somewhat smaller than that of niobium or tantalum. In most of the pegmatite minerals of niobium and tantalum into which antimony enters it is rather unlikely that it is present in the quinquevalent state but in the trivalent, if one considers the oxidation potentials involved. The ionic radius of Sb^{3+} must be larger than that of Sb^{5+} and is probably about 0.7 - 0.8A.

In a number of Norwegian pegmatite minerals, such as euxenite and samarskite, in which older chemical analyses report tin to be present (amounts around 1% SnO_2), it is quite likely that antimony has been the substance encountered.

Antimony in processes of weathering, soil formation, and in the sequence of sedimentary rocks

Our present knowledge of antimony in processes of weathering is derived exclusively from the oxidation zones of ore deposits. Sulphides of antimony are quite readily oxidized to oxygen compounds containing trivalent antimony, such as senarmontite, Sb_2O_3, and antimonites Only rarely is the oxidation stage of quinquevalent antimony attained as in romeite,

$$(Na,Ca)_2Sb_2(O,OH)_7.$$

No observations are available on the behaviour and fate of antimony during the weathering of ordinary rocks, and very little has been published concerning antimony in processes of soil formation. The only data at present available indicate a concentration of antimony and arsenic in ferruginous bauxites, and suggest that antimony in soils may associate with concentrations of ferric hydroxide. Nothing appears to be known about physiological effects resulting from a deficiency or excess of antimony in soils. It is, however, known to be one of the elements which have been concentrated in the ashes of certain coals.

Very little is likewise known about antimony in the sedimentary cycle. It probably occurs in both hydrolysate and oxidate sediments. In the latter it has been found in amounts roughly one fifth by weight of the arsenic.

There is some mineralogical indication that antimony (and in some cases arsenic also) can be accumulated with manganese dioxide sediments. Evidence for this is provided by the occurrence of numerous rare arsenates and antimonites in the manganese mines of Langban in Vermland, Sweden. The deposit is probably derived from a manganese oxidate sediment and most of the rare metallic constituents have probably been original constituents. A very interesting special feature of the Langban deposits is the occurrence of arsenic and antimony not as sulphides but in the form of highly oxidized compounds, derivatives of Sb_2O_3 or even Sb_2O_5, not as the results of subaerial weathering but because of the high oxidation potential of the surrounding manganese dioxide ores.

Antimony is also concentrated in some sulphidic sediments; the Permain copper-shale from Mansfield contains about 300 ppm Sb.

Antimony is not reported from sea water, but its occurrence in both oxidized and reduced marine sediments and in marine organisms makes it certain that in the course of the geochemical cycle it also passes through the ocean. I. and W. Noddack (1939) report that their search for antimony gave a negative result (less than 0.0005 ppm Sb). In all of nine marine animals they could detect antimony in amounts from 0.08-0.24 ppm Sb, the highest amounts, around 0.2 ppm, being found in a jelly-fish, an actinian, echinoderms, and fishes.

(3)

Arsenic

(a) As concentration range in Ontario tailings areas (121 samples) <20 - 75,400 ppm

(b) Average As concentration in Ontario tailings areas (120 samples) - 3,034 ppm

(c) Arsenic Background Data

NOTE: Also see Section A of this report

The geochemistry of arsenic involves a number of complications caused by the variable valency of the element. In its highest state of oxidation, i.e. As^{5+}, as in arsenates which are formally derived from the oxide As_2O_5, arsenic is very closely related to the phosphorus in phosphates, the ionic radii being As^{5+}0.47 A and P^{5+}0.34A, even though the bonds in the ortho-arsenate ion AsO_4^{3-} may be to a considerable extent covalent. The arsenates have a close crystallochemical and geochemical relationship to the corresponding phosphates and vanadates. In a few cases among the orthosilicates, structures analogous to arsenates have been observed, as in the case of garnet and berzeliite, which makes it likely that As^{5+} in some cases may replace Si^{4+} in minerals, provided that a sufficient oxidation potential prevails. The rare mineral ardennite provides an example. The rather rare sulpho-arsenates that are known only in a few ore deposits are closely related to corresponding sulpho-antimonates.

Little is yet known about the ionic radius of trivalent positive arsenic, which might be approximately measured in such a compound as AsF_3, but the distinct relationship between Sc_2O_3 and Mn_2O_3 and non-ionic As_2O_3 suggests an ionic radius not far from O.7A. Oxygen compounds of trivalent arsenic are not uncommon in the less highly oxidized zones of weathering of sulphide-arsenide ores. Sulpho-arsenites are common in the secondary cementation zones of many ore deposits.

In the native arsenic and arsenic-antimony alloys of some hydrothermal mineral deposits we assume that arsenic occurs in the un-ionized (atomic) state. The state of arsenic in the various arsenides of heavy metals, especially those of the iron group, is that of neutral atoms or deviates slightly towards arsenic anions. In these minerals there is a very close crystallochemical relationship between arsenic and sulphur as indicated by the very similar radii, as 1.18A, in such crystals. Therefore sulphide and arsenide minerals are very closely related. A closer approach to an anion-like state is probably attained by the arsenic in such compounds as the arsenides of the alkali and alkaline earth metals, e.g. calcium arsenide, which, however, do not occur in nature.

For the abundance of arsenic in rocks of the upper lithosphere we have not many analytical data. F. W. Clarke and H. S. Washington (1924) estimated the average amount to be 1 - 10 ppm As. G. Steiger (in Clarke, 1924) in a composite sample of 329 American magmatic rocks found 5.6 ppm As, and somewhat less in sedimentary rocks. In a number of recent sediments from the Atlantic B. Fr. v. Bulow (see Goldschmidt and Peters, 1934) found on an average 4 ppm As. As an average for the amount in the upper lithosphere 5 ppm As may not be very far from the truth. This order of abundance seems also to harmonize well with many recent data on arsenic in soils, but is possibly somewhat low.

Very little is known about the association of arsenic with any special types of magmatic rocks. One can only infer that the element in such rocks is present essentially in arsenides, for a great part hidden through replacement of the sulphur in sulphides of metals of the iron group, and that it probably in the main follows sulphur in the course of magmatic differentiation, the principal concentration being in the pyrrhotite ore deposits differentiated from gabbro and norite. The average amount of arsenic in such types of magmatic sulphide ores has been estimated to be at least 2,000 ppm.

There is only the single stable nuclide ^{75}As in nature. The relative cosmic and terrestrial abundances of the element are about the same.

The analysis of meteorites suggests that arsenic is essentially a thiophile element and this is strictly in accordance with its known modes of occurrence in the earth's crust, where it is found predominantly in sulphide ore bodies. It is a good example of an element, comparatively rare in the earth (2g/ton), which is in fact quite readily accessible on account of its concentration in such deposits. The small amount of arsenic in magmatic rocks is probably in the form of arsenides or sulpharsenides, 'hidden' in some of the sulphide minerals which are present to a small extent in such rocks. Arsenic occurs in the elemental state to a slight extent. There are many examples of binary compounds with metals, some of which have the structure of alloys.

There are sulphides and thio-salts of arsenic which exhibit the element in both its trivalent and pentavalent states. Natural arsenites are rare but pentavalent arsenic in the orthoarsenates is very common.

ARSENIC MINERALS

Name	Formula	Occurrence
Arsenic	As	Hydrothermal veins with Ag, Cu, and Ni ores
Domeykite	Cu_3As	As above with Cu ores
Realgar	As_4S_4	Hydrothermal veins and volcanic sublimates
Orpiment	As_2S_3	Hydrothermal veins and hot springs
Dimorphite	As_4S_3	Solfataric deposits
Lollingite	$FeAs_2$	Mesothermal veins with Cu and Fe sulphides
Arsenopyrite	FeAsS	Commonest arsenical mineral. Hydrothermal veins
Smaltite	$CoAs_2$	In Cu and Ni veins
Cobaltite	CoAsS	
Niccolite	NiAs	
Chloantite	$NiAs_2$	
Sperrylite	$PtAs_2$	Associated with igneous rocks - e.g., norite
Tennantite	Cu_3AsS_3	Metalliferous vein deposits
Sartorite	$PbAs_2S_4$	
Seligmannite	$CuPbAsS_3$ ...	
Enargite	Cu_3AsS_4	
Arsenolite	As_2O_3	Oxidized zones of hydrothermal veins

Arsenate minerals are very numerous, about seventy species having been described. They are to a large extent secondary products derived from the oxidation of primary arsenical ores in the upper zones of the deposits.

ARSENATE MINERALS

Name	Formula
Trichalcite	$Cu_3(AsO_4)_2 5H_2O$
Olivenite	Cu_2AsO_4OH
Hornesite	$Mg_3(AsO_4)_2 8H_2O$
Kottigite	$Zn_3(AsO_4)_2 8H_2O$
Mansfieldite	$AlAsO_4 2H_2O$
Rooseveltite	$BiAsO_4$
Trogerite	$HUO_2AsO_4 4H_2O$
Scorodite	$FeAsO_4 2H_2O$
Pharmacosiderite	$HFe_4(AsO_4)_3(OH)_4 6H_2O$
Erythrite	$Co_3(AsO_4)_2 8H_2O$
Mimetite	$Pb_5(AsO_4)_3Cl$

In residual sediments the amounts of arsenic are presumably very small.

Concerning hydrolysate sediments we may refer to investigations by B. Fr. v. Bulow in fifty-seven samples of marine bottom muds collected during the Meteor expedition, the average arsenic content of which was 4 ppm. In a composite of 235 samples of mud from the river Mississippi F. W. Clarke and G. Steiger (1914) found 3 ppm As. E. C. Sullivan found 8 ppm As in a composite of fifty-one samples of red deep-sea clay (see Clarke and Steiger, 1914). A considerable amount of the arsenic entering the sedimentary cycle from the weathering of magmatic rocks, and also of arsenic from volcanic exhalations and hot springs, is thus precipitated together with the hydrolysate sediments.

A much more conspicuous concentration of arsenic has taken place, however, in connection with the precipitation of ferric hydroxide, and it is possible that the fixation of arsenic in marine muds takes place largely as a result of their ferric hydroxide content. A great number of oxidate sediments of iron have been investigated including samples of oxidate sediments from marine and fresh waters. The amounts of arsenic in fifteen samples of Mesozoic marine iron ores from France, Germany, and south Sweden were in three cases about 700 ppm, in two cases 100 ppm As, the other ten cases giving intermediate results. In four American hematite ores amounts between 70 and 500 ppm As were found. In metamorphosed sedimentary iron ores containing coarsely crystalline hematite the arsenic seemed to have been removed by some leaching process.

In various glauconitic sediments arsenic was found up to about 70 ppm. but was sometimes apparently not detectable. In sedimentary manganese ores from Kutais-Tchiaturi in the Caucasus only 70 ppm As were found. In freshwater oxidate deposits from Finland less arsenic was present in the manganese sediments than in ferric hydroxide.

Arsenic in processes of weathering and soil formation

Our information about the geochemistry of arsenic in processes of weathering is mainly derived from the study of zones of oxidation of sulphide and arsenide deposits. Besides the two crystalline modifications of As_2O_3, a few arsenites are formed together with a multitude of simple and complex arsenates, such as pharmacosiderite,

$$Fe_3((AsO_4)_2(OH_3))5H_2O$$

and erythrite,

$$Co_3(AsO_4)_2 8H_2O.$$

Generally, arsenates are formed and found in oxidation zones in contact with the free oxygen of the atmosphere. Quite exceptionally they may be stable in deep horizons of the earth, in metamorphic rocks, when superoxides are present to furnish the necessary oxidation potential; examples are found in the many arsenates and antimonates which are associated with the metamorphic manganese ores of Vermland in Sweden. Here, the manganese minerals such as braunite, Mn_7SiO_{12}, furnish the oxidation potential for the formation of a great variety of arsenate and antimonate minerals.

Arsenic is precipitated from many of its soluble compounds, often very effectively, by the hydroxide of ferric iron (a well known antidote in cases of arsenic poisoning) and it is probable that arsenic in soils is in many cases precipitated in the same way. In the uppermost aerated parts of soils arsenic is probably present as the arsenate ion.

There have been made careful chemical determinations of arsenic in the different horizons of various soils. An unweighted average of the arsenic contents for the various horizons of eleven soils in the U.S.A. (Slater, Holmes, and Byers, 1937) gives 7.5 ppm As, the range being 4.5 to 13.0 ppm. Within each soil the variations in many cases indicate a concentration in the illuvial horizon, but a few exceptions to that rule have been found. It is interesting that the average is very near to the average arsenic content of the upper lithosphere. These soils have never been treated with arsenical chemicals. More recent data on arsenic in soils from the U.S.A. (and Mexico) are found in a publication by Williams and Whetstone (1940).

(4)

Barium

(a) Ba concentration range in Ontario tailings areas (121 samples) 5 - 313 ppm

(b) Average Ba concentration in Ontario tailings areas (121 samples) - 26 ppm

(c) Barium Background Data

NOTE: Also see Section A of this report

There are seven stable isotopes of barium in nature:

^{130}Ba = 0.101%	^{136}Ba = 7.81%
^{132}Ba = 0.097%	^{137}Ba = 11.32%
^{134}Ba = 2.42 %	^{138}Ba = 71.66%
^{135}Ba = 6.59 %	

There do not appear to be any significant aspects of natural nuclear chemistry as far as barium is concerned.

BARIUM MINERALS

Name	Formula	Occurrence
Psilomelane	$(Ba,Mn)Mn_4{}^{IV}O_8(OH)_2$	
Witherite	$BaCO_3$	Hydrothermal veins
Bromlite	$BaCa(CO_3)_2$	
Sanbornite	$BaSi_2O_5$	
Gillespite	$BaFeSi_4O_{12}$	
Celsian	$BaAl_2Si_2O_8$	
Cymrite	$BaAlSi_3O_8OH$	Rare rock minerals,
Harmotome	$BaAl_2Si_6O_{16}6H_2O$	etc.
Banalsite	$Na_2BaAl_4Si_4O_{16}$	
Hyalophane	$(K,Si,Ba,Al)AlSi_2O_8$	
Leucosphenite	$Na_3CaBaBTi_3Si_9O_{29}$	
Gorceixite	$BaAl_3P_2O_7(OH)_7$	
Baryte	$BaSO_4$	
Barytoanglesite	$(Ba,Pb)SO_4$	Hydrothermal veins
Nitrobarite	$Ba(NO_3)_2$	

The geochemistry of barium, atomic number 56, in igneous rocks and their minerals is characterized to rather a large extent by its relationship to potassium. The ionic radii of divalent barium (1.43 A) and univalent potassium (1.33 A) are sufficiently similar to allow barium to be captured by potassium minerals, as is also the case with the divalent ion of strontium (1.27 A). On the other hand, contrary to what is the case with strontium, the difference in ionic radii between barium and calcium (1.06 A) is such that the barium ions are usually able to enter calcium minerals only in extremely small amounts, the amount of BaO in any igneous calcium minerals scarcely ever exceeding about 100 ppm and in most cases being much less.

The average content in the igneous rocks of the earth's crust was calculated by von Engelhardt to be 480 ppm BaO. For the sediments his calculation leads to 430 ppm BaO, making use of V. M. Goldschmidt's values for the amounts of the various sediment types. The agreement between the data for BaO in igneous and sedimentary rocks is thus quite satisfactory.

BARIUM IN FELDSPARS FROM IGNEOUS ROCKS

		BaO ppm
Plagioclases	Bytownite rock, Sogn, Norway	30-100
	Labradorite rock	60
	Albite from pegmatite, Amelia Court House, Virginia	1-3
Potash feldspar from early and main crystallization of igneous rocks	Porphyritic sanidine from trachyte, Drachenfels	16,000
	Porphyritic orthoclase from porphyritic granite, Karlsbad	4,900
	Cryptoperthite from larvikite, Hovland, near Narvik, Norway	3,000-10,000
	Cryptoperthite from larvikite, Fredriksvern, Norway	1,000-3,000
Potash feldspars from pegmatites	Feldspar from pegmatitic ditroite, Ditro	520
	Microcline microperthite from nepheline syenite pegmatite, Laven, near Langesund, Norway	90
	Amazonite from granite pegmatite, Uto Sweden	190
	Microcline from granite pegmatite, Ytterby, Sweden	30-100
	Microcline from granite pegmatite, Kragero, Norway	10-30
	Amazonite from granite pegmatite, Miask, Urals, U.S.S.R.	3-10

We may compare the contents of barium in the various types of igneous rock from the quantitative spectrographic analyses made by von Engelhardt, the data for plutonic and volcanic rocks of the same family being averaged:

Rock Family (plutonic or volcanic)	BaO ppm
Pyroxenite and peridotite	3
Gabbro (incl. anorthosite) and basalt	70*
Diorite and andesite	260
Granite and liparite	480
Nepheline syenite and phonolite	580
Syenite and trachyte	1,800
Leucite rocks	1,000-4,000

* There is much more BaO in alkaline gabbros, such as essexites, and alkaline basalts.

A most characteristic feature is the increase from the pyroxenite and peridotites, with often less than 1 ppm BaO,** through gabbro and diorite to the residual magmas of granite and nepheline syenite, with 500 or 600 ppm.

The preference of barium for potash feldspars and for 'early' porphyritic potash feldspars is most marked, as is the scarcity of barium in potash feldspars from 'late' pegmatites.

Barium in the Weathering Cycle

Concerning the geochemistry of barium in the processes of weathering and soil formation there can be no doubt that the barium of igneous rocks is dissolved on the decomposition of its host minerals and brought into circulation, in aqueous bicarbonate solutions for the most part.

The barium in sea water amounts to about 0.5 ppm; a higher content, on account of the concentration of sulphate ions in sea water, would probably be reduced by precipitation of barium sulphate.

Various processes eliminate solute barium from the sedimentary circulation. Most important is probably the precipitation of the very insoluble $BaSO_4$, which we find often as conspicuous concretions in many marine hydrolysate sediments, e.g. shales. Sometimes rather important concentrations of $BaSO_4$ are found in the sediments associated with sedimentary sulphides, as in the Meggen deposits of Westphalia. Another process for precipitation of barium takes place in oxidate sediments, especially in those rich in manganese dioxide. This kind of precipitation is possibly connected with the absorption of barium cations to the negatively charged colloidal particles of the manganese precipitate, the amount of BaO often being 1% or more.

** Because barium, radius 1.43 A, is unable to enter the lattices of magnesium silicates, the radius of the magnesium ion being only 0.78 A.

Considerable amounts of barium are also found in many hydrolysate sediments, also possibly held by absorption, and usually amounting to 200-600 ppm BaO in marine sediments, and as low as 3-10 ppm or even less in bauxites.

In marine limestones the amounts of barium are generally very low - 10-30 ppm as a rule, more rarely up to 200 ppm BaO. In dolomite the content of barium is usually extremely low, owing to the same processes that cause a depletion in strontium in the course of dolomitization.

In marine evaporate sediments barium is found only in very inconsiderable amounts, in most cases no greater than 1-10 ppm BaO. This low percentage is about equivalent to the barium content of sea water, which gives to the salts 1-3 ppm BaO.

The following average amounts have been found by von Engelhardt:

	BaO ppm
Sandstones	200
Shales	500
Limestones	100

Barium is one of the very many less common elements which may be considerably concentrated in certain coal ashes. The amounts of BaO in such ash may reach 1,000-10,000 ppm and over. The concentration may be analogous to the rather common enrichment of so many elements in the leaves of plants and consequently forest litter.

Barium is toxic to higher animals and there is no indication that it performs any useful function in any kind of organism. Marine organisms which show some enrichment in strontium do not likewise absorb barium. Some plants growing near barium deposits accumulate a certain amount of the element, probably adventitiously, and this has been proposed as the basis of a possible method of biogeochemical prospecting.

(5)

Bismuth

(a) Bi concentration range in Ontario tailings areas (121 samples) <10 - 2,020 ppm

(b) Average Bi concentration in Ontario tailings areas (120 samples) - 17 ppm

(c) Bismuth Background Data

NOTE: Also see Section A of this report

Natural bismuth consists of the single nuclide ^{209}Bi. There are in addition a number of short-lived isotopes of bismuth in the various families of natural radioactive elements.

It is now confirmed that ^{209}Bi is in fact radioactive with the very low half-life of 2×10^{17} years and decays to ^{205}Tl by a-activity. It is probable that the bulk of terrestrial bismuth is non-radiogenic.

BISMUTH MINERALS

Name	Formula
Bismuth	Bi
Maldonite	Au_2Bi
Bismuthinite	Bi_2S_3
Guanajuatite	$Bi_2(Se,S)_3$
Tellurbismuth	Bi_2Te_3
Tetradymite	Bi_2Te_2S
Joséite	Bi_4TeS_2
Galenobismutite	$PbBi_2S_4$
Beegerite	$Pb_6Bi_2S_9$
Gladite	$CuPbBi_5S_9$
Cosalite	$CuPb_7Bi_8S_{22}$
Bismite	Bi_2O_3
Bismutite	$(BiO)_2CO_3$
Eulytine	$Bi_4Si_3O_{12}$
Bismutotantalite	$BiTaO_4$
Rooseveltite	$BiAsO_4$
Arsenobismite	$Bi_2(AsO_4)(OH)_3$
Pucherite	$BiVO_4$

In addition up to 20 species of sulpho-salts have been described

Geochemistry

Bismuth is a rare element with a crustal abundance of about 0.2g/ton and with pronounced thiophile affinities. Unlike antimony it tends to separate in the earlier high-temperature stages of hydrothermal activity associated with granitic intrusions. The free element is not uncommon and may be associated with gold. Apart from the sulphides and sulpho-salts, compounds of bismuth with selenium and tellurium are rather characteristic. Being more electropositive than antimony bismuth can form a number of independent oxy-salts, including even a silicate. Most of the minerals, which are generally found in veins associated with granite rocks, are comparatively rare and local.

As in the case of antimony, the geochemical data concerning bismuth are scanty and the general outlines of the geochemistry can by provided not from a great number of analytical data, but only from some general principles and from mineralogical experience.

For the amount of bismuth in the upper lithosphere various estimates have been published:

	Bi ppm
F. W. Clarke and H. S. Washington (1924)	0.01-0.1
G. Berg (1925)	0.034
I. and W. Noddack (1934)	0.07
V. M. Goldschmidt (1938)	at least 0.2

Bismuth enters rather regularly into the apatites of magmatic rocks, the trivalent bismuth ion being captured here because of its similarity in radius to divalent calcium:

Bi^{3+} 1.09 A, Ca^{2+} 1.06 A.

Bismuth, like yttrium, probably also enters other early calcium minerals from magmatic sources and will certainly be found in many, perhaps most, of the minerals of the rare elements, especially those of the yttrium earths, in a number of which it has already been found.

In rocks of the upper lithosphere bismuth is distinctly chalcophil; in all known bismuth deposits of economic importance the element is found in sulphide minerals or in secondary alteration products of sulphides and related compounds. But it is quite certain that in the upper lithosphere the element has also distinctly lithophil properties and is found as a normal constituent of oxygen compounds. Not only does it replace calcium in apatites, but it is also found as one of the major constituents in a number of the niobates and tantalates of granite pegmatites, and, as a minor constituent, probably in many minerals of the yttrium earth elements.

Bismuth in processes of weathering and of soil formation

As is the case with so many other rare chalcophil elements our knowledge of the behaviour of bismuth in processes of weathering is limited to observations in the oxidation zone of ore deposits. Well known products of oxidation are, for instance, bismite, Bi_2O_3, hydroxycarbonates, vanadates, and although very rarely, even silicates of bismuth, but no higher stage of oxidation in bismuth minerals than the trivalent is known. The necessary oxidation potentials for the formation of compounds of higher oxides are not met in nature and might be expected only in (alkaline) nitrate soils under arid desert conditions. It is noteworthy that the oxidation potential necessary for the formation of oxygen compounds of the quinquevalent element rises considerably in the series from arsenic , through antimony, to bismuth. Oxygen compounds of quinquevalent arsenic are common, those of antimony are rarely formed, and those of bismuth are unknown in nature. This may be connected with decreasing strength of the covalent bonds within the ion $(XO_4)^{3-}$.

Nothing is as yet known about the fate of bismuth in soil formation, except that it collects in ferruginous bauxites, and it might be looked for in other concentrations of ferric minerals in soils.

Bismuth is among the elements known to collect in the ashes of certain coal seams together with many other rare elements. It is quite likely that corresponding accumulations may be discovered in the litter and uppermost humus layers of forest soils.

(6)

Boron

(a) B concentration range in Ontario tailings areas (121 samples) 2 - 435 ppm

(b) Average B concentration in Ontario tailings areas (121 samples) - 97 ppm

(c) Boron Background Data

NOTE: Also see Section A of this report

There are two stable isotopes of this element in nature:

^{10}B = 18.98% ^{11}B = 81.02%

The lighter of the two isotopes can absorb slow neutrons readily and it may be supposed that the reaction

$$^{10}B + n = {}^{7}Li + a$$

can take place to a slight extent where boron compounds occur in the presence of suitable neutron sources such as radium with beryllium. The extent of this reaction in nature is, however, probably much too small for it to have any appreciable effect on the ratio of the two isotopes.

On account of the relatively large difference in mass, it is possible that some degree of fractionation of the isotopes may take place in nature. This has not, however, yet been detected with any certainty.

BORON MINERALS

Name	Formula	Occurrence
Avogadrite	KBF_4	Volcanic deposits
Ferruccite	$NaBF_4$	
Sassolite	$B(OH)_3$	
Kernite	$Na_2B_4O_7{\cdot}4H_2O$	Evaporites
Borax	$Na_2B_4O_7{\cdot}10H_2O$	
Kaliborite	$KMg_2B_{11}O_{19}{\cdot}15H_2O$	
Colemanite	$Ca_2B_6O_{11}{\cdot}5H_2O$	
Ulexite	$NaCa_5B_5O_9{\cdot}8H_2O$	
Eremeyerite	$AlBO_3$	Granitic rocks
Sinhalite	$MgAlBO_4$	
Ludwigite	$(Mg,Fe)_2Fe^{3+}BO_5$	Metamorphic rocks
Fluorborite	$Mg_3BO_3(F,OH)_3$	Evaporites
Boracite	$Mg_6B_{14}O_{26}Cl_2$	
Searlesite	$NaBSi_2O_6{\cdot}H_2O$	
Danburite	$CaB_2Si_2O_8$	Rock Minerals
Dumortierite	$(Al,Fe)_7BSi_3O_{18}$	
Leucosphenite	$Na_3CaBaBTi_3Si_9O_{29}$	

Tourmaline $(Na,Ca)(Li,Mg,Fe,Al)_3(Al,Fe^{3+})_6B_3Si_6O_{27}(O,OH,F)_4$

Geochemistry

There are in the main three aspects of the geochemistry of this element. They can be stated as follows:

(a) Occurrence in the late stages of magmatic crystallization.
(b) Occurrence in volcanic emanations.
(c) Occurrence in evaporite deposits.

(a) Boron is an oxyphile and lithophile element and it is characterized by small atomic and ionic dimensions. The radius of the atom for tetrahedral co-ordination is 0.89 A and the radius of the ion is only 0.20 A. The corresponding values for silicon are 1.17 and 0.41 A, respectively and the values are of some significance. Boron has very little tendency to enter the silicate lattices of common rock forming minerals and therefore it tends to remain until the last stages of magmatic crystallization.

The most abundant and virtually the only important boron mineral in rocks is tourmaline, and as noted above it is a very complex silicate with considerable variation in ionic content. Tourmaline typically crystallizes in granites and granite-pegmatites and as a result of the weathering of these rocks it provides the small but necessary boron content of soils and sediments. It appears that boron can replace silicon in a few silicate minerals apart from tourmaline and in the case of danburite and datolite there are discrete BO_4 tetrahedra in a framework of SiO_4 tetrahedra. There is no doubt that the great part of the boron of the earth's crust is concealed in silicate minerals but as boron is much less readily accepted into silicate lattices than aluminum it tends to separate in the later stages of magmatic crystallization.

(b) The presence of boron in volcanic gases and waters is rather common and it seems that it is closely related to the presence of a volatile boron compound which reacts with water and various rock minerals before it can be actually emitted at the surface of the earth.

The fact that the commonest boron mineral, tourmaline, contains fluorine and that several fluorborates are found near volcanic vents points strongly to the compound being boron trifluoride BF_3. This is further confirmed by the presence of volatile boric acid in fumarolic gases and in some localities the presence also of hydrogen fluoride - e.g., Valley of Ten Thousand Smokes, Alaska. It is probable that the boron content of sea water, of various saline lakes and of the solid saline deposits may be related to the volcanic emanations of boron compounds.

(c) The evaporite deposits of boron compounds are encountered in several parts of the world; they are mostly derived from lake waters which have received volcanic products as noted above.

Although sea water contains a perceptible amount of borate the oceanic salt deposits in general have not provided useful sources of the element at the present time.

Boron in Igneous Rocks

Concerning the amounts of boron in rocks, a number of data are available from the investigations of Goldschmidt and Peters and Landergren, which are briefly summarized in the following paragraphs and table:

Rock	B_2O_3 ppm
Granites (composite of 14)	10
Gabbros (composite of 11)	10
Nepheline syenites (composite sample)	10
Plateau basalt	5
Basalts (composite of 22)	5

Plutonic rocks

In all plutonic rocks investigated the same amount of B_2O_3 was found, viz. 10 ppm B_2O_3, corresponding to 3 ppm B. The specimens included a composite sample of eleven gabbro rocks and one of fourteen granites, both from Germany, a composite sample of twenty-two nepheline syenites poor in ferromagnesian minerals, from various parts of the world, an essexite, a ditroite, and a biotite granite from the Oslo district. (Landergren (1945) gives the boron content of seventeen Swedish granites and gneisses as 10-100 ppm B_2O_3 and suggests that the Goldschmidt and Peters values are somewhat low. The results of Sahama (1945) and Nockolds and Mitchell (1948) are similar and it would appear that appreciable amounts of boron are present in basic rocks).

Volcanic rocks

The volcanic rocks gave somewhat more varied results. Basalts from Oregon and Washington, U.S.A., as well as a German basalt, gave 5 ppm B_2O_3, corresponding to 1-2 ppm B. The same result was obtained with pantellerite from Pantelleria, south of Sicily, and with obsidian from Iceland. Andesite from western Java had 5-10 ppm B_2O_3, and andesite from Santorin, Greece, 10 ppm B_2O_3. The highest amount found was in liparite from Lipari, Italy, viz. 100 ppm B_2O_3 or 30 ppm B.

Minerals from igneous rocks

The boron contents of micas were suprisingly low; the same amount (5 ppm B_2O_3) was found in muscovite, phlogopite, biotite and lepidomelane. In amazonite feldspar no boron was detected;

cancrinite froma nepheline syenite pegmatite of the Langesund Fjord contained 10 ppm B_2O_3; amphiboles contained up to 50 ppm B_2O_3. Iron ores of magmatic origin were found to be very poor in boron; in five Swedish magnetite ores no boron was detected; in two of four magnetite-ilmenite ores and ilmenite ores of Sweden and Norway 5 ppm were found. Landergren found that most of the Swedish magmatic iron ores (161 out of 202 ores) belonged to the lowest order of his classifications, with less than 30 ppm B_2O_3.

Biochemical Aspects of the Geochemistry of Boron

The geochemistry of boron is intimately connected with biological problems. We shall first summarize some of the results of Goldschmidt and Peters (1932) for marine organisms.

Boron could be detected in the calcareous or siliceous parts of nearly all the organisms investigated. Radiolarian ooze contained about 500 ppm B_2O_3, the skeleton of a siliceous sponge 1,000 ppm B_2O_3, fossil Mesozoic siliceous sponges 50-1,000 ppm. Fossil radiolarian rock of Lias age from the Tyrol contained 100 ppm B_2O_3. Fresh water silica diatoms gave no detectable amount, nor did the silica, geyserite, from the Great Geyser in Iceland.

In quartz of hydrothermal or magmatic origin no detectable amounts of boron were found. Therefore, the presence of boron in a siliceous sediment, in absence of clastic tourmaline, might be taken as evidence of marine biochemical origin.

In practically all calcareous skeletons or shells or marine organisms boron could be detected. Some of the highest amounts were found in the calcium carbonate of corals, in both Hexacoralla and Octocoralla. The amounts of B_2O_3 were usually about 500 ppm, rarely as high as 1,000 ppm or as low as 10 ppm. In Silurian and Devonian fossil corals 5-500 ppm B_2O_3 were encountered, the lower limit most frequently.

In marine bivalves, as well as in cephalopods, only small amounts of boron were found, ranging from 5 to 10 ppm B_2O_3; the only gastropod studied gave no detectable amounts. In a sample of globigerina ooze 50 ppm were found. Some non-calcareous and non-siliceous integuments and skeletons were also studied. The mineral ash of the shells of two recent brachiopods contained 100 ppm B_2O_3 and the ash of the spongin skeleton of the common sponge 5,000 ppm.

Data reported on the boron contents of marine algae and seaweeds are still in part conflicting and vary between wide limits. The data for boron in the ashes of Laminaria saccharina and Fucus vesiculosus vary from a few tenths of a ppm B_2O_3 up to 10,000 ppm. In a specimen of Lithopyllum cristatum 500 ppm B_2O_3 were found. Further investigations on boron in marine plants are highly desirable, especially in connection with the boron in oil waters.

The importance of boron in organic life on land was first realized through the discovery of W. E. Brenchley and K. Warrington (1927) that boron, in very amounts, is indispensable for the culture of certain plants, especially root crops. This discovery has initiated numerous investigations in a number of countries on the effect of boron on various crops, on the distribution and availability of boron in soils, on the presence of boron in certain fertilizers, and also on the harmful effects of excess boron, especially in fruit growing. There already exists an extensive literature on the subject

In the ash of land plants boron is an ordinary constituent in amounts of 100-5,000 ppm B_2O_3. In the ash (0.5% ash) of beech wood 5,000 ppm have been found; in the ash from the bark of the same tree (6.1% ash) there were only 1,000 ppm. The tree was growing in soil from weathering basalt in Adelebsen, south Hanover, Germany - a soil which contained 10 ppm B_2O_3; the concentration of boron in the inorganic constituents had thus been increased 500 times in the wood ash.

In nearly all cases the biochemical function of boron in plants is still unknown. From the following example one might assume that the ability of boric acid to form rather stable, strongly acidic, complexes with sugars is of some importance. The botanist Th. Schmucker (1932) investigated the nectar in the flowers of tropical water lilies for an unknown component which was active in the fertilization of the pollen. This component was found to be boron, the ash of the nectar containing 1% B_2O_3; an artificial mixture of sugars with 1% B_2O_3 had the same effect on the pollen.

Of course from an agricultural point of view, only that part of the total boron in soils which is available to plants is of importance and, therefore, in soil investigations the standard chemical methods employed refer to the boron contents of the soil extract. The boron contained in an extremely resistant mineral such as tourmaline can be considered somewhat inaccessible to plants.

Considering the variable distribution of boron in the various rock types it is clear that the available boron of soils will vary to a great extent with the parent material. Goldschmidt and Peters (1932) found about 5-10 ppm total B_2O_3 in soils derived from the weathering of granites and basalts. In soils derived from marine sediments or from regions recently covered by the sea up to 100 ppm total B_2O_3 were found.

Concerning the distribution of water-soluble boron in soils the following data may be quoted:

	B ppm
Italian soils (L. Salto, 1939-40)	0.06-1.90
Hawaiian soils (T. Tanda and L. A. Dean, 1940 and 1942)	0.20-3.20
Soils of Illinois and Georgia, U.S.A. (E.E. DeTurk and L.C. Olsen, 1941)	0.01-1.22
Russian soils (S. I. Sinyakova, 1939)	0.19-1.10

(7)

Cadmium

(a) Cd concentration range in Ontario tailings areas (121 samples) 0.3 - 155 ppm

(b) Average Cd concentration in Ontario tailings areas (119 samples) - 2.4 ppm

(c) Cadmium Background Data

NOTE: Also see Section A of this report

Eight stable isotopes of cadmium exist in nature:

^{106}Cd = 1.215%	^{112}Cd = 24.07%
^{108}Cd = 0.875%	^{113}Cd = 12.26%
^{110}Cd = 12.39%	^{114}Cd = 28.86%
^{111}Cd = 12.75%	^{116}Cd = 7.58%

Geochemistry

With an estimated abundance of 0.2g/ton for the earth's crust, cadmium may be considered one of the rarer elements. It is, however, fairly accessible, mainly as a by-product. Independent cadmium minerals are little more than mineralogical curiosities. The most important are:

Pribramite	(Zn,Cd)S
Greenockite	CdS
Cadmium hausmannite	$CdMn_2O_4$
Otavite	$CdCO_3$

Cadmium is mainly distributed in the earth as a 'guest' ion or atom. The tetrahedral covalent radius of cadmium is only 13% greater than that of zinc and it can therefore enter the sphalerite structures in which zinc sulphide crystallizes. On the other hand, the cadmium ion being 31% larger than the zinc ion, in oxidized compounds it is unlikely that cadmium would be associated with zinc.

The geochemistry of cadmium is not yet very completely known, but an outline can be given of some of its essential features. The following table gives a review of several estimates of the amounts of the element in the upper lithosphere.

	Cd ppm
Magmatic rocks, F. W. Clarke and H. S. Washington (1924)	0.1-1
Upper lithosphere, V. M. Goldschmidt (1938)	0.5
American magmatic rocks, E. B. Sandell and S. S. Goldich (1943)	0.18

Of these data, those of Sandell and Goldich are based on quantitative chemical determinations of both zinc and cadmium in eight samples of igneous rocks, three of the samples being composites. The ratio of cadmium to zinc was found to be rather uniform, on the average about 1:500 by weight. This gives an average amount of cadmium in magmatic rocks of 0.18 ppm if we accept the average amount of zinc to be 80 ppm as given by the same authors.

Crystallochemical relations between cadmium and other elements are governed by the size relationships of the radii. The ionic radius of cadmium in octahedral coordination is 1.02 A, quite close to those of sodium 0.98 A and calcium 1.06 A. We may therefore expect that some cadmium will enter into minerals of calcium and sodium such as the plagioclases, just as zinc enters ferrous or ferromagnesian minerals. The rather close similarity between the ionic radii of calcium and cadmium is shown by the entry of spectrographically detectable amounts of cadmium into the bytownite feldspar of anorthosite, that is, into early crystallizates of gabbroid magmas, and also into monoclinic augite pehnocrysts of basalts. Another consequence of these size relations is that the crystal structures of cadmium oxide and carbonate closely resemble the corresponding calcium compounds, and in a most interesting manner. The distribution of cadmium between zinc minerals and calcite at Franklin Furnace is such that the cadmium enters the calcite in preference to zincite and franklinite.

It is also possible that the similarity in ionic radii between cadmium and divalent manganese may have geochemical consequences

Mn^{2+}	Cd^{2+}	Ca^{2+}
0.91	1.03	1.06 A

The ionic radius of cadmium is just between those of manganese and calcium and it would be interesting to study the distribution of cadmium between manganous silicates (such as rhodonite, $MnSiO_3$) and calcite in the ores from Franklin Furnace.

Cadmium, because of the electron structure of its atoms, has a tendency to enter into tetrahedral coordination, although not as strongly as does zinc. The tetrahedral covalent radius of cadmium is 1.48 A and accounts for the isomorphous substitution of cadmium for zinc in zinc sulphide.

Cadmium has a strong affinity for sulphur and the relations of the free energies of formation of sulphides and oxides (or other ionic compounds) of cadmium and zinc are such that cadmium is more chalcophil than zinc at low and moderate temperatures. Cadmium sulphide, therefore, often remains as a yellow incrustation when sphalerite is subjected to weathering. It is well known from elementary analytical chemistry that cadmium, unlike zinc, can be precipitated from strongly acid solutions. When the amount of sulphur is insufficient to accommodate both cadmium and

zinc as sulphides then cadmium will be preferentially concentrated in the sulphides.

The ionic radius of cadmium should enable this element to enter crystals even of lead sulphide minerals. A curious example is known of cadmium in a galena described by I. Oftedal (1941), where contamination by sphalerite seems to be excluded. It might be worth while studying the various sulpho-salts of lead for the possible presence of cadmium. Oftedal found such a case in a sulpho-bismuthite of lead with 100 ppm Cd from a high temperature hydrothermal deposit in northern Norway.

Cadmium in Magmatic Rocks and Their Minerals

Very few data have been published concerning the distribution of cadmium in the various magmatic rocks and minerals.

CADMIUM IN NORWEGIAN SPHALERITES

		Cd ppm
Nepheline syenite pegmatites	(4)	400
Pyro-metasomatic, Oslo district	(24)	2,000
High hydrothermal, Caledonian mountain range	(19)	2,000
Medium and low hydrothermal, Caledonian mountain range	(14)	2,500
Medium hydrothermal, Kongsberg, etc.	(15)	6,000
Medium and low hydrothermal, S. Norway	(15)	6,000

The lowest amount observed, 10 ppm was in the nepheline syenite pegmatite from Greenland, the five highest amounts in Norwegian low and medium hydrothermal deposits were from 10,000 to 45,000 ppm Cd, the last determination being checked by quantitative chemical analysis (4.43% Cd). Of course the proportion of cadmium to zinc must be dependent upon various local factors, one of which is the available amount of zinc sulphide. In accordance with this, the experience is that sphalerites containing more than 1% Cd contained only 1 or 2 % Fe. In any case the correlation with temperature seems to be good within the range of c. 100° up to perhaps 600° C. Neglecting the occurrences in pegmatites, which are of scientific interest only, the proportion by weight of cadmium to zinc in sphalerites is between 1:300 and 1:100: that is, much more cadmium in proportion to zinc than the ratio 1:500 found for magmatic rocks by Sandell and Goldich. This difference seems to indicate that much more zinc than cadmium is retained in non-sulphide minerals, a consequence in agreement with the more chalcophil nature of cadmium.

That lead minerals also may take up cadmium is evidenced by cadmium bearing galena from granite pegmatite and by a high temperature hydrothermal sulpho-bismuthite of lead. I. and W. Noddack (1931 a) record 300 and 10 ppm Cd from hydrothermal lead selenide and lead telluride respectively and 180 ppm Cd from manganese sulphide, alabandine, as well as from several hydrothermal tetrahedral sulphides and sulpho-salts such as chalcopyrite, enargite, tetrahedrite, and germanite.

The distribution of cadmium in various sulphide minerals may perhaps in future provide a means of estimating the temperature and other physico-chemical conditions during the formation of hydrothermal ore deposits. The hexagonal cadmium sulphide, greenockite, and the corresponding cubic modification are found in hydrothermal deposits, often in their zones of oxidation and cementation.

Cadmium in Processes of Weathering and Soil Formation

Our present knowledge of the geochemistry of cadmium in processes of weathering is derived exclusively from the study of oxidation zones of ore deposits. As mentioned above, cadmium can remain as sulphide even when its host mineral sphalerite has been dissolved, but under conditions of strong oxidation cadmium forms oxidized minerals, such as CdO and $CdCO_3$. Some data on their lattice constants may illustrate their similarity to corresponding compounds of calcium and divalent manganese

	a		a	α (alpha)
CaO	4.80 A	$CaCO_3$	6.36 A	46^{o} 6'
CdO	4.69	$CdCO_3$	6.11	47^{o} 46'
MnO	4.44	$MnCO_3$	5.84	47^{o} 46'

Practically nothing is known about cadmium in processes of soil formation. We may assume that in many respects it behaves rather like calcium, with the exception that under reducing conditions in soils, where H_2S is evolved, cadmium will be precipitated as the very insoluble CdS. (Malyuga (1941) records 1.7 and 45 ppm Cd for two semi-arid soils of the U.S.S.R.).

Cadmium belongs to the elements which are found concentrated in coal ashes (up to 50 ppm) and perhaps, like zinc, may be concentrated in forest litter and in forest humus.

(8)

Calcium

(a) Ca concentration range in Ontario tailings areas (121 samples) 98 - 15,300 ppm

(b) Average Ca concentration in Ontario tailings areas (121 samples) - 4,089 ppm

(c) Calcium Background Data

NOTE: Also see Section A of this report

The similarity in the ionic radii of divalent calcium (1.06 A) and univalent sodium (0.98 A) leads to a crystallochemical relationship between these two elements somewhat similar to that which exists between barium and potassium. In the case of barium and potassium the relationship results in a concentration (by capture) of the rare element barium in early potassium minerals from igneous rocks. In the case of calcium and sodium, calcium is not a rare element (in which case it would be concentrated in early sodium minerals), the average atomic abundance of calcium and sodium being practically equal, and therefore in this respect the analogy is not strict. This aspect can be conveniently worded as follows: sodium ions are admitted into calcium minerals, and increasingly so in late crystallizations of calcium minerals.

The following are the most important calcium minerals of igneous rocks:

A. Calcic monoclinic pyroxenes, essentially metasilicates of calcium and magnesium+ferrous iron, of the type $CaMg(SiO_3)_2$.

B. The plagioclase feldspars, isomorphous mixtures of anorthite $CaAl_2Si_2O_8$ and albite $NaAlSi_3O_8$. The increased strength of ionic bonding between the doubly charged calcium cation and the complex anion $(Al_2Si_2O_8)^{2-}$ compared with the strength of bonding between singly charged sodium and the complex anion $(AlSi_3O_8)^-$ causes anorthite to have a much higher melting point (1,500° C.) than albite (1,118° C.), and gives rise to the well known melting and crystallization diagram of the plagioclases. This peculiarity results in the familiar sequence from calcic to sodic plagioclases in the fractional crystallization of igneous magmas, and the zoning of plagioclase crystals.

C. Monoclinic amphiboles, various isomorphous mixtures related to $Mg_5Ca_2Si_8O_{22}(OH,F)_2$.

D. Apatite (in nearly all igneous rocks, though generally only in small amounts), essentially isomorphous mixtures of $Ca_5(PO_4)_3F$ and $Ca_5(PO_4)_3Cl$.

E. In rocks formed from residual magmas, such as nepheline syenites, syenites, granites, and granodiorites, we find small amounts of sphene, $CaTiSiO_5$, and minerals of the epidote-orthite group; and in nepheline syenites and genetically related rocks we may find the carbonate-silicate cancrinite, $3NaAlSiO_4CaCO_3$, and even primary calcite $CaCO_3$, in considerable amounts, and also a number of zirconosilicates essentially of calcium and sodium, e.g. catapleiite, eudialyte, and eucolite. A certain amount of lime often enters into such feldspathoids as nepheline and the various minerals of the sodalite group.

F. Finally, mention may be made of a few calcium minerals which are found exclusively in certain rare basic rocks related to gabbro and basalt but richer in alkali metals, namely, melilite, essentially an isomorphous mixture of akermanite, $Ca_2MgSi_2O_7$, gehlenite, $Ca_2Al_2SiO_7$, and sodamelilite, $Na_2Si_3O_7$. Other calcic minerals in the same type of rock are monticellite, $CaMgSiO_4$, and perovskite, $CaTiO_3$.

Calcium is of comparatively high abundance cosmically and on the earth it appears to be more abundant than magnesium. This is true only for the crust for in the earth as a whole the value of 0.61% places it well below magnesium (17%).

As with magnesium, the number of calcium-bearing minerals is so large that only a representative list is presented here.

CALCIUM MINERALS

Name	Formula	Occurrence
Oldhamite	CaS	Meteorites
Portlandite	$Ca(OH)_2$	Alteration product
Fluorite	CaF_2	H.T. veins, rocks
Chlorocalcite	$KCaCl_3$	Volcanic sublimates
Colemanite	$Ca_2B_6O_{11}5H_2O$	Evaporites
Calcite	$CaCO_3$	Sedimentary rocks, mineral veins
Aragonite	$CaCO_3$	
Nitrocalcite	$Ca(NO_3)_2nH_2O$	Efflorescence in caves
Wollastonite	$CaSiO_3$	Igneous rocks
Rankinite	$Ca_3Si_2O_7$	Secondary minerals of igneous & metamorphic rocks
Larnite	$CaSi_2O_4$	
Tobermorite	$Ca_5Si_6O_{16}(OH)_24H_2O$	
Pectolite	$NaCa_2Si_3O_8OH$	
Anorthite	$CaAl_2Si_2O_8$	Igneous rocks

Name	Formula	Occurrence
Laumontite	$CaAl_2Si_4O_{12}4H_2O$	Zeolitic
Datolite	$CaBSiO_4OH$	
Whitlockite	$Ca_3(PO_4)_2$	Phosphate
Hydroxyapatite	$Ca_5(PO_4)_3OH$	deposits
Apatite	$Ca_5(PO_4)_3F$	Rock
Chloroapatite	$Ca_5(PO_4)_3Cl$	minerals
Anhydrite	$CaSO_4$	Evaporites
Gypsum	$CaSO_4 2H_2O$	Evaporites
Scheelite	$CaWO_4$	H.T. veins
Lautarite	$Ca(IO_3)_2$	Evaporites

Calcium as a rock-forming element tends to be concentrated in the basic and intermediate types of igneous rocks and there are several reasons for this:

1. Calcium forms a feldspar, anorthite $CaAl_2Si_2O_8$, which readily forms a series of isomorphous mixtures with the pure soda feldspar albite $NaAlSi_3O_8$ - these constitute the plagioclase series. They are the typical feldspars of basic and intermediate igneous rocks and extend even to some extent to the granites.

The pure lime feldspar melts at 1550° C whereas soda feldspar melts at 1118° C so that calcic feldspars will tend to crystallize first from a magma and the outer layers of large feldspar crystals will always tend to be richer in albite.

2. Calcium ions readily enter certain ino-silicates together with magnesium and ferrous iron - these are the pyroxenic and amphibolic minerals which are very characteristic of basic and intermediate rocks such as gabbro, basalt, dolerite, andesite, and diorite.

3. Residual calcium in igneous magmas can often be taken into various accessory minerals, some of which may be fairly abundant. They include apatites, sphene $CaTiSiO_5$, perovskite $CaTiO_3$, cancrinite $3NaAlSiO_4 CaCO_3$, and even calcite itself.

The ubiquity of calcium ions in igneous rocks is no doubt due largely to their radius (0.99 A) which is such that a large number of other cations can deputize for calcium and vice versa. The following are examples:

Na = 0.98 A, Mn^{2+} = 0.91 A, Sm^{2+} = 1.26 A
Sr = 1.27 A, and the lanthanides - e.g., Lu = 0.99 A

In practice calcium minerals largely act as hosts for rarer cations

(9)

Chlorine

(a) Cl concentration range in Ontario tailings areas (121 samples) - <10 - 380 ppm

(b) Average Cl concentration in Ontario tailings areas (121 samples) - < 32 ppm

(c) Chlorine Background Data

NOTE: Also see Section A of this report

The amount of chlorine in magmatic rocks is generally very low, amounting on the average, according to F. W. Clarke and H. S. Washington (1924) to 0.05% Cl. (L. S. Selivanov (1940) gives an unweighted average of 314 ppm Cl for the wide range of rocks in which he determined both chlorine and bromine. The lowest value, 10 ppm, was found in a quartz syenite, the highest, 980 ppm, came from a syenite.

Only in very exceptional cases in plutonic and volcanic rocks rich in sodalite does the amount of chlorine rise to several per cent. by weight of the rock.

The cause of the scarcity of chlorine in magmatic rocks is essentially the volatility and solubility of very many chlorine compounds

The most significant chlorine-bearing minerals are chlorapatite and sodalite. They are essentially rock minerals and probably account in the aggregate for a very considerable proportion of the chlorine in the earth's crust. Relatively little chlorine is carried by such minerals as micas and amphiboles which often have on the other hand a notable fluorine content.

(10)

Chromium

(a) Cr concentration range in Ontario tailings areas (121 samples) 19 - 1,040 ppm

(b) Average Cr Concentration in Ontario tailings areas (121 samples) - 155 ppm

(c) Chromium Background Data

NOTE: Also see Section A of this report

There are four stable isotopes of this element in nature:

^{50}Cr = 4.31% ^{53}Cr = 9.55%

^{52}Cr = 83.76% ^{54}Cr = 2.38%

The estimated crustal abundance of chromium is 200 g/ton and the analyses of meteorites indicate that it should be markedly thiophile. However, no sulphur compounds of chromium are known in the earth and they could only be formed under much lower redox potentials than obtain in the crust.

Chromium is rather widely distributed in the earth and is found in both its trivalent and hexalent but not in its divalent state. The most important concentrations depend on the refractory character and rather high density of certain oxide minerals of chromium which separate at an early stage of magmatic crystallization and may form segregations in basic and ultrabasic rocks. These oxide minerals are of great stability and were considered by Goldschmidt to be largely covalent in structure. The majority of the terrestrial minerals carry the element in the trivalent state and they are not very numerous. However, owing to similarity in ionic size, some replacement of Fe^{3+} and Al^{3+} ions by Cr^{3+} can take place and chromium is therefore found in small amounts in a number of common silicate minerals.

It appears that most of the chromium in the earth's crust is in the form of spinellid minerals of which the most important is the common ore mineral chromite $FeCr_2O_4$.

Chromium is the usual colouring matter of the green beryl called emerald. The chromium content of emeralds is of the order of 1% of Cr_2O_3. It is presumed that part of the aluminium of the mineral is replaced by chromium in its trivalent state.

CHROMIUM MINERALS

Name	Formula	Occurrence
Magnochromite	$MgCr_2O_4$	Accessory minerals in ultrabasic and basic igneous rocks
Chromite	$FeCr_2O_4$	
Picotite	$(Fe,Mg)(Al,Cr)_2O_4$	
Stichtite	$Mg_6Cr_2CO_3(OH)_{16}4H_2O$	In altered ultrabasic rocks
Babertonite	$Mg_6Cr_2CO_3(OH)_{16}4H_2O$	
Uvarovite	$Ca_3Cr_2(SiO_4)_3$	
Tarapacaite	K_2CrO_4	In caliche deposits, Chile
Lopezite	$K_2Cr_2O_7$	
Crocoite	$PbCrO_4$	
Vauquelinite	$(Pb,Cu)_3((Cr,P)O_4)_2$	In oxidized zones of lead veins
Beresovite	$Pb_6(CrO_4)_3O_2CO_3$	
Dietzeite	$Ca_2(CrO_4)(IO_3)_2$	Caliche deposits, Chile

Chromium in the formal valency state of Cr^{6+} is met with in the chromates which only occur rather rarely as mineral substances. It is evident that the high oxidation potential needed to raise the element to this state is but rarely attained in nature.

The subject of chromium in hydrothermal deposits has been somewhat neglected, and it has been assumed that chromium is not much involved in hydrothermal mineral formation because minerals of trivalent chromium are mostly very insoluble (covalent as well as electrostatic bonds). However, rather much evidence has been brought forward to show that even many important chromite deposits connected with magnesian rocks of magmatic origin may owe their final concentration to hydrothermal processes operative in the formation of hydrous magnesian silicates (serpentine and talc) from olivine and pyroxenes.

On a small scale several, if not very many, examples are known of the geochemical mobility of chromium in hydrothermal processes. Such are the hydrothermal formation of chromium chlorites from chromite ores and the formation of calcium-chromium garnet, uvarovite ($Ca_3Cr_2Si_3O_{12}$), at the expense of chromite. Many interesting instances have been found in connection with the pyrite-chalcopyrite ores of Outukumpo in Finland, where there occur chromium garnet, chromium pyroxenes and amphiboles, and chromium epidote (tawmawite), in some way probably related to a dolomite rock which may represent a transformed magnesian silicate mass.

The presence of chromiferous mica (fuchsite, mariposite) in hydrothermal deposits may be taken as evidence for a certain mobility of the trivalent chromium ions. This is also suggested by the chromiferous beryllium minerals of the Urals, although in these cases it has been rather the beryllium ion which has been added to chromiferous rocks by residual solutions from granite magmas.

Chromium in Processes of Weathering and of Soil Formation

Under intensive oxidation chromium is oxidized from the trivalent to the sexivalent state, thus forming the chromate ion $(CrO_4)^{2-}$. This results in an intensive mobilization of the otherwise rather immobile chromic ion by transformation into an easily soluble anion. The chromate ion may then either be precipitated by the cations of certain heavy metals, especially lead, giving rise to such conspicuous minerals as crocoite ($PbCrO_4$) or, for instance, be taken up in the lead molybdate wulfenite ($PbMoO_4$). In the absence of considerable amounts of solute lead ions the chromate ion may migrate in soil solutions and become concentrated in products of evaporation, as in the nitrate deposits of the Atacama desert in Chile. In these much of the chromate ion is probably present as an isomorphous substituent in sulphates. Among separate chromate minerals from these deposits we have mentioned the mineral dietzeite, $Ca_2(CrO_4)(IO_3)_2$, a 'double salt' of chromate and iodate of calcium.

Chromates are considered to be very rare minerals. For crocoite only a few occurrences are known; a scarcity that is out of proportion to the abundance of both chromium and lead. The reason is, of course, to be sought in the very different conditions for the concentration of the two metals. Large concentrations of chromium are limited exclusively to certain early crystallizates of gabbroid magmas such as peridotites and pyroxenites, whereas lead is concentrated in residual solutions from granite magmas. Crocoite can thus be formed only when both processes of differentiation have taken place at the same spot, as when younger hydrothermal solutions of lead compounds intersect chromiferous magnesian silicate rocks and when local conditions permit oxidation of the chromium. This has, for instance, been the case at the well-known localities for crocoite crystals in the Urals and at Mount Dundas in Tasmania.

A certain, if restricted, geochemical mobility may thus be ascribed to the chromic ion, although it is probably somewhat less than that of 6-coordinated aluminum. This mobility is indicated by the formation of ionic chromic compounds from chromite ore at low hydrothermal temperatures, a process which probably extends downwards in the temperature scale until the processes of weathering are reached. The formation of conspicuous though thin coatings of green or violet chromium chlorites and related minerals on weathered chromite ores should be noted.

(11)

Cobalt

(a) Co concentration range in Ontario tailings areas (121 samples) 1 4,060 ppm

(b) Average Co concentration in Ontario tailings areas (117 samples) - 83 ppm

(c) Cobalt Background Data

NOTE: Also see Section A of this report

Cobalt is the least abundant member of the iron triad as far as the earth's crust is concerned, the estimated value being 23g/ton.

The number of independent cobalt minerals is not very large. It has some tendency to enter silicate structures but on account of similarity of atomic and ionic radii to iron it is fairly commonly present as a 'concealed' element in sulphide minerals. Most of the workable deposits of cobalt are in fact subsidiary to copper. Most of the mineral compounds exhibit the lower oxidation state Co^{2+} but a few seem to contain the Co^{3+} ion. The much higher potential (1.84 V) needed to effect this oxidation than in the case of iron, explains the paucity of natural cobaltic compounds.

COBALT MINERALS

Name	Formula
Linnaeite	Co_3O_4
Cattierite	CoS_2
Smaltite	$CoAs_2$
Cobaltite	CoAsS
Heterogenite	CoO.OH
Sphaerocobaltite	$CoCO_3$
Lusakite	$(Fe,Co,Mg)_4Al_{18}Si_8O_{46}(OH)_2$
Erythrite	$Co_3(AsO_4)_2 8H_2O$
Roselite	$Ca_2(Co,Mg)(AsO_4)_2 2H_2O$
Bieberite	$CoSO_4 7H_2O$

Copper

(a) Cu concentration range in Ontario tailings areas (121 samples) 10 - 18,700 ppm

(b) Average Cu concentration in Ontario tailings areas (118 samples) - 310 ppm

(c) Copper Background Data

NOTE: Also see Section A of this report

Two stable isotopes of copper exist:

$^{63}Cu = 69.1\%$

$^{65}Cu = 30.9\%$

There is no great significance in their behaviour in nature as at present ascertained.

Terrestrial Abundance

The average figure is 45g/ton for the earth's crust and the more acidic rocks (granitic) are much poorer in the metal at about 15g/ton. The average for basic rocks is as much as 149g/ton or about ten times that in the acidic rocks. Some sediments such as limestones are low in copper but argillaceous sediments are often considerably enriched in it.

Copper does not contribute appreciably to rock-forming silicate minerals and seems to occur in rocks mainly in the form of sulphides.

Copper Minerals

Copper is characteristically thiophile and the largest concentrations of the element are in the form of various sulphur compounds but it also forms stable compounds of many types in nature. There is a marked propensity for copper to form basic salts and very many of the natural oxy-salts of the metal are of this type.

Upwards of 150 copper minerals have been described of which a limited number actually constitute important ores of the metal.

From the point of view of mode of occurrence these very numerous minerals can be classed into two broad groups. Native copper together with its various sulphides and compounds with the metalloids are the chief constituents of 'primary' deposits. The oxy- and halide salts are in general encountered in the upper oxidized zones of cupriferous deposits. Owing to the characteristic green or blue colour of so many of these compounds,

mere traces of copper are often readily observed, but they are frequently too poor or restricted in size to be of commercial interest.

Geochemistry

The primary copper minerals which are either simple or complex sulphides are unlike the silicates and other oxy-salts in being predominantly covalent in character and in many cases they exhibit metallic or sub-metallic properties.

In spite of the variety of compounds the disulphide $CuFeS_2$ chalcopyrite is the most abundant ore mineral. However, owing to the very widespread nature and great variety of workable copper deposits, the metal is extracted from a larger number of different minerals than perhaps any other metal.

Mineralogically the ores can be divided into four groups:

(a) Native copper
(b) Sulphides
(c) Oxidized ores
(d) Complex ores

The most valuable ores in general are the sulphides. The complex ores, however, are often valuable as they may also be sources of silver, gold, etc. Although the actual copper content from rock analyses indicates that basic (gabbroic) types of rocks are the most cupriferous, yet most of the localized copper ores are associated with rather acidic intrusive rocks such as quartz-monzonites.

As previously indicated, where copper is present in appreciable quantity in a rock magma it tends to associate with sulphur and iron and not with oxygen and silicon, so that the relatively few deposits of magmatic type are mainly of sulphides, particularly the several complex sulphides of iron and copper. It is probable that most of the other kinds of copper minerals are of the hydrothermal type - i.e., have been deposited from aqueous solutions within the temperature range 500°-50° C and also of course in some cases under considerable pressure. Recent Russian work indicates that solubility of sulphides under such conditions is greater than was once thought.

Oxidation

The primary minerals of copper being essentially sulphides, when the ore body in course of geological changes is brought near to the surface it may well happen that a considerable amount of it comes above the water table. In this zone, within which water, oxygen, and carbon dioxide are available, most of the oxidation products are formed. As most ores contain pyrite, FeS_2, it is suggested that oxidation in accordance with the

reaction

$$FeS_2 + 7O + H_2O = FeSO_4 + H_2SO_4$$

provides a source of sulphuric acid. Then the reaction

$$6FeSO_4 + 3O + 3H_2O = 2Fe_2(SO_4)_3 + Fe(OH)_3$$

provides ferric sulphate which can react with copper sulphide as follows:

$$CuFeS_2 + 2Fe_2S(O_4)_3 = CuSO_4 + 5FeSO_4 + 2S$$

$$Cu_2S + Fe_2(SO_4)_3 = CuSO_4 + FeSO_4 + CuS$$

$$CuS + Fe_2(SO_4)_3 = CuSO_4 + 2FeSO_4 + CuS$$

Cupric sulphate in solution, not being susceptible to oxidation and being less readily hydrolysed than the iron salts, is fairly mobile and could travel both laterally and vertically. On reaching an environment of higher pH it would form various basic sulphates and thus be immobilized. The presence of phosphates in solution derived from the action of sulphuric acid on the mineral apatite often present in igneous rocks could provide the means of formation of copper phosphate minerals. The carbonates would form when the pH was high enough and when carbonic acid became available either from the atmosphere or more often from limestone rocks.

COPPER MINERALS

Name	Formula
Native copper	Cu
Domeykite	Cu_3As
Chalcocite	Cu_2S
Covelline	CuS
Berzelianite	Cu_2Se
Bornite	Cu_5FeS_4
Chalcopyrite	$CuFeS_2$
Chalcopyrrhotine	$CuFe_4S_5$
Cubanite	$CuFe_2S_3$
Valerite	$Cu_2Fe_4S_7$
Tennantite	Cu_3AsS_3
Tetrahedrite	Cu_3SbS_3
Cuprite	Cu_2O
Tenorite	CuO
Namaqualite	$Cu_2Al(OH)_7 2H_2O$
Nantokite	CuCl

Name	Formula
Eriochalcite	$CuCl_2 2H_2O$
Atacamite	$Cu_2Cl(OH)_3$
Malachite	$Cu_2CO_3(OH)_2$
Azurite	$Cu_3(CO_3)_2(OH)_2$
Dioptase	$CuSiO_2(OH)_2$
Chrysocolla	$CuSiO_3 2H_2O$
Pseudomalachite	$Cu_5(PO_4)_2(OH)_4$
Turquoise	$CuAl_6(PO_4)_4(OH)_8 5H_2O$
Olivenite	$Cu_2AsO_4(OH)$
Uzbekite	$Cu_3(VO_4)_2 3H_2O$
Chalcantite	$CuSO_4 5H_2O$
Antlerite	$Cu_3SO_4(OH)_4$
Brochantite	$Cu_4SO_4(OH)_6$
Linarite	$(Pb,Cu)_2SO_4(OH)_2$
Lindgrenite	$Cu_3(MoO_4)_2(OH)_2$
Cuprotungstite	$Cu_2WO_4(OH)_2$
Gerhardtite	$Cu_2NO_3(OH)_3$

(13)

Fluorine

(a) F concentration range in Ontario tailings areas (121 samples) 78 - 2,520 ppm

(b) Average F concentration in Ontario tailings areas (117 samples) - 264 ppm

(c) Fluorine Background Data

NOTE: Also see Section A of this report

Only the single nuclide ^{19}F exists in nature.

The actual terrestrial abundance of fluorine as of the other halogens is a matter of some doubt. The fluorine content of different rocks varies quite widely even for the same rock type. The figure of 700 g/ton should therefore be accepted with some reserve. It is, however, clear that fluorine is a comparatively abundant element in the earth's crust.

The most electronegative of the elements, fluorine is normally found as its anion (F^-=1.33A) which is very nearly the same size as the ions OH^- and O^{2-} and it can therefore enter into a considerable variety of minerals.

FLUORINE MINERALS

Name	Formula	Occurrence
Villiaumite	NaF	In cavities in alkalic rocks
Fluellite	$3AlF_3 \cdot 4H_2O$	H.T. hydrothermal veins
Cryolithionite	$Li_3Na_3Al_2F_{12}$	In granite pegmatite with cryolite
Cryolite	Na_3AlF_6	As above - very local
Sellaite	MgF_2	In dolomite rocks & fumarolic
Fluorite	CaF_2	In hydrothermal veins & accessory in granite rocks
Cerfluorite	$(Ca,Ce)F_{2-3}$	Pegmatitic mineral
Matlockite	PbFCl	Hydrothermal lead veins
Ferruccite	$NaBF_4$	Fumarolic
Hieratite	K_2SiF_6	Fumarolic
Fluorapatite	$Ca_5(PO_4)_3F$	Accessory rock mineral, widespread
Fluoborite	$Mg_3BO_3(F,OH)_3$	Hydrothermal mineral
Topaz	$Al_2SiO_4(OH,F)_2$	Accessory in greisenized granites

Much of the fluorine in igneous rocks is present in the form of the mineral fluorapatite $Ca_5(PO_4)_3F$, which in the pure state carries 3.77% F. But most apatites have some replacement of F^- by OH^- and the fluorine content is usually less. Chlorine is also commonly present and there are continuous isomorphous series between the three minerals fluorapatite, chlorapatite, and hydroxyapatite.

It was at one time considered that in acid rocks fluorapatite was the characteristic mineral wheras in basic rocks chlorapatite was said to predominate. In considering rock analyses it is quite frequently found that the fluorine (and chlorine) content is appreciably in excess of the amount corresponding to the known apatite content of the rock. This is because fluorine in particular is present also in various silicates where it replaces OH^- ions in such minerals as the micas and amphiboles.

There is replacement by chlorine as well as fluorine, but in much smaller amounts because, no doubt, the larger Cl^- ion (radius 1.81 A) can less easily enter the lattices. The mineral sphene $Ca(TiO)SiO_4$ also sometimes has some replacement of oxygen by fluorine. The following are examples of silicates containing variable small amounts of fluorine:

Leucophane	$(Ca,Na)_2BeSi_2(O,OH,F)_7$
Meliphane	$(Ca,Na)_2Be(Si,Al)_2(O,F)_7$
Norbergite	$Mg_3SiO_4(F,OH)_2$
Fluorbiotite	$K(Mg,Fe)_3AlSi_3O_{10}F_2$
Clinohumite	$Mg_9Si_4O_{16}(F,OH)_2$

These fluorine-bearing minerals are numerous, over fifty species having been described. They often contain metals such as lithium, beryllium, and the rare earths. They are generally accessory rock minerals or occur in the residuals of magmatic crystallization - e.g., in pegmatites. The fluorine in the original magma has probably considerable fluxing properties and favours the highly fluid melts or solutions which are characteristic of the formation of pegmatites.

In many cases it is possible to account completely for the distribution of the fluorine in a rock.

Thus, to quote an analysis given by Koritnig for the Brocken granite, Harz Mountains:

Total fluorine by analysis (%)	0.086%
7.0% biotite with 0.415% F (%)	0.029%
0.11% fluorite (by difference) (%)	0.053%
Apatite, F content (%)	0.004%
TOTAL	0.086%

The weathering of rocks containing fluorine compounds is susceptible to different climatic conditions and to the nature of the original fluorine-bearing minerals. Thus the weathered products of a Cornish granite (quoted by Butler) show that the fluorine content has been halved so that much of the fluorine has been leached out whereas, in the case of a syenite from Norway, the derived soil seems to have retained practically all of the fluorine of the original rock.

The fluorine content of soils is connected with the apatite content, suggesting that the actual component is fluorapatite to a large extent. The actual fluorine values for soils are very variable but the average is of the order of 200 ppm. Clays and argillaceous rocks generally seem to be enriched in fluorine, often in excess of 1000 ppm which is in part due to apatite and more particularly to micaceous minerals. The true clay minerals, e.g., kaolinite and bentonite - often contain considerable amounts of fluorine (2000 - 4000 ppm).

(14)

Iron

(a) Fe concentration range in Ontario tailings areas (121 samples) 2,770 - 375,000 ppm

(b) Average Fe concentration in Ontario tailings areas (121 samples) - 87,952

(c) Iron Background Data

NOTE: Also see Section A of this report

There are four stable isotopes of the element in nature:

^{54}Fe = 5.84% ^{57}Fe = 2.17%
^{56}Fe = 91.68% ^{58}Fe = 0.31%

IRON MINERALS

Name	Formula
Minerals of Mainly Magmatic Origin	
Iron	Fe
Pyrrhotine	FeS (non-stoichiometric)
Pyrite Marcasite	FeS_2
Wüstite	FeO
Magnetite	Fe_3O_4
Fayalite	Fe_2SiO4
Riebeckite	$Na_2Fe_3^{2+}Fe_2^{3+}Si_8O_{22}(OH)_2$
Aegirine	$NaFe^{3+}Si_2O_6$
Olivine	$(Mg,Fe)_2SiO_4$
Hypersthene	$(Mg,Fe)SiO_3$
Hedenbergite	$CaFeSi_2O_6$
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$
Biotite	$K_2(Mg,Fe,Al,Fe^{3+})_{4-6}(Si,Al)_8O_{20}(OH)_4$
Augite	$(Ca,Mg,Fe^{2+},Fe^{3+},Al)(Si,Al)O_3$
Hornblende	$(Ca,Na,K)_{2-3}(Mg,Fe,Fe^{3+},Al)_5(SiAl)_8O_{22}(OH)_2$
Minerals of Hydrothermal Deposits	
Achavalite	FeSe
Löllingite	$FeAs_2$
Arsenopyrite	FeAsS
Hercynite	$FeAl_2O_4$
Siderite	$FeCO_3$
Vivianite	$Fe_3(PO_4)_2 8H_2O$

Name	Formula
Minerals of Hydrothermal Deposits (continued)	
Phosphosiderite	$FePO_4 2H_2O$
Scorodite	$FeAsO_4 2H_2O$
Melanterite	$FeSO_4 7H_2O$
Butlerite	$Fe^{3+}SO_4(OH).2H_2O$
Minerals of Sedimentary Rocks	
Hematite	Fe_2O_3
Siderite	$FeCO_3$
Goethite Lepidocrocite	FeO(OH)
Pyrite	FeS_2
Minerals of Metamorphic Rocks	
Cordierite	$(Mg,Fe)_2Al_4Si_5O_{18}$
Epidote	$Ca_2(Al,Fe)_3Si_3O_{12}(OH)$
Garnet	$Fe_3Al_2(SiO_4)_3$
Minerals of Evaporites and Fumarolic Deposits	
Lawrencite	$FeCl_2$
Douglasite	$K_2FeCl_4 2H_2O$
Rinneite	$K_3NaFeCl_6$
Ludwigite	$(Mg,Fe)_2Fe^{3+}BO_5$

Iron is of high abundance in the earth. For the crust the value is 5% and for the earth as a whole, as deduced from physical properties, nature of meteorites, etc., it is quoted as 35% by weight. It would appear that iron is in fact a typical siderophile element. But the affinity of iron for sulphur is considerable, large masses of iron sulphide minerals exist and the thiophile character of the element cannot be ignored. In the crust as a whole iron is in combination with oxygen and enters freely into silicate minerals; it is therefore also lithophile. Iron is an essential element in living organisms and must be reckoned as biophile also. It is thus a ubiquitious element. It does not, however, make any appreciable show in the atmosphere except in compounds present in volcanic dust, and for various reasons its content in the hydrosphere is rather low.

Primary iron silicate minerals are extremely numerous, particularly in igneous rocks. They are characteristic of the more basic types and the iron content generally falls with increasing silica content but the relationship between the two is not simple. It is notable that the ratio of ferrous to ferric iron tends to decrease as indicated in the following table:

	Dunites	Gabbros	Diorites	Granites
Silica(%)	40	48	57	70
Fe^{2+}	4.4	4.8	3.5	1.4
Fe^{3+}	2.0	2.2	2.2	1.1
Fe^{2+}/Fe^{3+}	2.2	2.2	1.6	1.3

In spite of the large number of iron silicate minerals there are in fact few of these which are simple silicates of iron alone.

The Fe^{2+} ion, radius 0.74 A, is somewhat larger than the Mg^{2+} ion (0.66 A), and although diadochy between the two is not uncommon, yet the complete replacement of magnesium by ferrous iron is rather rare, the most important example being the case of the orthosilicate series

$$Mg_2SiO_4\text{-}Fe_2SiO_4$$

The two iron pyroxenes $FeSiO_3$ are not characteristic of magmatic rocks and seem to have been formed under low temperature conditions. They are comparatively rare. The mineral hypersthene never contains more than 90% $FeSiO_3$, the remainder being $MgSiO_3$. It appears that $FeSiO_3$ is not stable at high temperatures and an artificial melt of this composition separates:

$$2FeSiO_3 = Fe_2SiO_4 + SiO_2$$

The Fe^{2+} ion cannot replace Ca^{2+} in feldspars for thermochemical reasons but it is possible for Fe^{3+} to replace Al^{3+} in these minerals. Thus ferriferous orthoclase has been reported containing up to 2.88% Fe_2O_3. This is a rare occurrence, however, and it seems probable that the pink colour so often encountered in feldspars is due to exsolution of Fe^{3+} ions and decomposition to Fe_2O_3. The iron silicates of sedimentary rocks are mainly glauconite and chlorite. They characteristically impart a green colour to sediments which contain them. In both cases they contain both ferrous and ferric ions. Chloropal is a ferriferous clay mineral in which Fe^{3+} largely replaces Al^{3+}. Pure ferric silicates are of doubtful occurrence in nature. In metamorphic rocks the minerals cordierite, anthophyllite, tremolite, biotite, and glaucophane are the chief silicates containing iron.

(15)

Lead

(a) Pb concentration range in Ontario tailings areas (121 samples) <1 - 6,900 ppm

(b) Average Pb concentration in Ontario tailings areas (113 samples) - 66 ppm

(c) Lead Background Data

NOTE: Also see Section A of this report

The geochemistry of lead in the minerals and rocks of the upper lithosphere is dominated by its properties both as a chalcophil and as a lithophil element. As a chalcophil element it is found mostly as the sulphide galena, PbS, and in related compounds with selenium and tellurium, as well as in a great number of sulpho-salts, where it acts as a cation. The occurrence of lead in combination with sulphur and related elements is by far the most important from an economic point of view.

But lead is also a lithophil element occurring in a large number of rock-forming minerals. Its ionic radius (Pb^{2+} 1.32 A) makes it possible for lead to replace strontium (1.27 A), barium (1.43 A), potassium (1.33 A), and in certain minerals even calcium (1.06 A). Accordingly, divalent lead commonly occurs in the potassium minerals of silicate rocks and also in apatite. Ionic salts of divalent lead are found in the oxidation zone of sulphide ore deposits. These salts include carbonates, sulphates, chromates, phosphates, and vanadates. In oxidation zones in which high oxidation potentials prevail, as in hot arid climates, the oxide of quadrivalent lead is found. This has the rutile structure, Pb^{4+} having a smaller ionic radius than Pb^{2+} (Pb^{4+} 0.89 A).

The occurrence and distribution of lead in magmatic rocks is well known. F. W. Clarke and H.S. Washington (1924) estimated the average amount to be 20 ppm Pb; G. von Hevesy (1932) got an average of 16 ppm; E. B. Sandell and S. S. Goldich (1943) found as an average for fifty-four North American magmatic rocks 14 ppm Pb. An investigation by F. W. Clarke and G. Steiger (1914) on a mixture of American magmatic rocks gave only 7.5 ppm Pb, but this is probably on the low side, as mentioned by von Hevesy.

For sedimentary rocks spectrographic determinations by the author and Dr. H. Hörmann gave about 20 ppm Pb in composite samples of arenaceous shales and about 5-10 ppm in limestones, data which agree well with the results of von Hevesy and Sandell and Goldich on magmatic rocks. We can therefore accept 16 ppm Pb as the average amount in the upper lithosphere.

Lead as a divalent ion is closely associated with strontium which has a very similar ionic radius. It is captured in potassium minerals, and small amounts are found in magmatic calcium minerals. The monoclinic augites of magmatic rocks, mainly $Ca(Mg,Fe)Si_2O_6$, often contain 3-10 ppm Pb. Magmatic apatite has a great capacity for rare ions, even if their radius differs notably from that of calcium, and it is therefore a common host mineral for lead and may contain up to 50 ppm. In some cases the lead in apatite may be the final product of decay of radioactive thorium, ionium, or uranium. The considerable amount of Pb found by von Hevesy in a dunite from North Carolina was probably due to some contamination of his material.

In magmatic anhydrous potassium minerals lead is found quite universally. Potash feldspar may contain 5-100 ppm Pb, the highest amounts usually occurring in early crystallizations of the feldspar. Here also the similar ions of strontium and divalent europium have been concentrated. The geochemical data leave no doubt that the distribution of lead in magmatic rocks is generally controlled by the laws of crystal chemistry, lead ions being concentrated in the potassium minerals, especially the early crystallizates. It would be desirable to have more detailed investigations on the distribution of lead in minerals of the mica group and in feldspathoids.

LEAD MINERALS

Name	Formula
Native Lead	Pb
Galena	PbS
Sartorite	$PbAs_2S_4$ (about 37 related species)
Bournonite	$PbCuSbS_3$ (about 25 related species)
Seligmannite	$CuPbAsS_3$
Litharge	PbO
Minium	Pb_3O_4
Plattnerite	PbO_2
Matlockite	PbFCl
Cotunnite	$PbCl_2$
Cerussite	$PbCO_3$
Hydrocerussite	$Pb_3(CO_3)_2(OH)_2$
Phosgenite	$Pb_2CO_3Cl_2$
Leadhillite	$Pb_4SO_4(CO_3)_2(OH)_2$
Alamosite	$PbSiO_3$
Plumbogummite	$PbAl_3(PO_4)_2(OH)_5H_2O$
Pyromorphite	$Pb_5(PO_4)_3Cl$
Mimetite	$Pb_5(AsO_4)_3Cl$
Vanadinite	$Pb_5(VO_4)_3Cl$
Anglesite	$PbSO_4$
Wulfenite	$PbMoO_4$
Crocoite	$PbCrO_4$
Stolzite	$PbWO_4$

Magnesium

(a) Mg concentration range in Ontario tailings areas (120 samples) 98 - 36,600 ppm

(b) Average Mg concentration in Ontario tailings areas (117 samples) - 9,861 ppm

(c) Magnesium Background Data

NOTE: Also see Section A of this report

MAGNESIUM MINERALS

Name	Formula	Occurrence
Periclase	MgO	Metamorphic minerals
Brucite	$Mg(OH)_2$	
Spinel	$MgAl_2O_4$	
Sellaite	MgF_2	Volcanic, etc.
Bischoffite	$MgCl_2 \cdot 6H_2O$	Evaporite deposits
Carnallite	$KMgCl_3 \cdot 6H_2O$	
Suanite	$Mg_2B_2O_5$	
Inderite	$Mg_2B_6O_{11} \cdot 15H_2O$	
Fluorborite	$Mg_3BO_3(F,OH)_3$	
Boracite	$Mg_6B_{14}O_{26}Cl_2$	
Magnesite	$MgCO_3$	Altered rocks, minerals, etc.
Nesquehonite	$MgCO_3 \cdot 3H_2O$	
Lansfordite	$MgCO_3 \cdot 5H_2O$	
Hydromagnesite	$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$	
Dolomite	$CaMg(CO_3)_2$	
Nitromagnesite	$Mg(NO_3)_2 \cdot 6H_2O$	Evaporite deposits
Forsterite	Mg_2SiO_4	Rock minerals
Enstatite	$MgSiO_3$	
Chrysotile	$Mg_3Si_2O_5(OH)_4$	
Talc	$Mg_3Si_4O_{10}(OH)_2$	
Ackermanite	$MgCa_2Si_2O_7$	
Diopside	$MgCaSi_2O_6$	
Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$	
Olivine	$(Mg,Fe)_2SiO_4$	
Hypersthene	$(Mg,Fe)SiO_3$	
Pyrope	$Mg_3Al_2Si_3O_{12}$	
Phlogopite	$KMg_3AlSi_3O_{10}(OH)_2$	
Bobierrite	$Mg_3(PO_4)_2 \cdot 8H_2O$	Guano deposits
Struvite	$NH_4MgPO_4 \cdot 6H_2O$	
Kieserite	$MgSO_4 \cdot H_2O$	Evaporite deposits
Epsomite	$MgSO_4 \cdot 7H_2O$	

Magnesium is characteristically the cation which goes into the orthosilicate minerals of which forsterite is the pure species and olivine the more general form. These minerals are nesosilicates which possess a very compact structure, great resistance to high pressures and a relatively high melting point. All these factors favour their early separation from a magma and they are therefore met with especially in the deep-seated igneous rocks such as dunite and peridotite of which the earth's mantle is thought to be composed. The ordinary basic rocks of basaltic and gabbroic type which characterize the deeper zones of the crust also contain magnesian silicates, usually associated with ferrous iron. Examples are the pyroxenes and amphiboles, both of which classes are inosilicates, tending to form chain structures, less compact than the orthosilicates. The magnesian minerals of the upper crust are generally of the phyllosilicate class, tending to extended two-dimensional structures, good examples being talc, serpentine, and phlogopite mica. The garnets are especially connected with metamorphic rocks; they are orthosilicates well adapted in structure to high pressure conditions.

For the above reasons it is clear that a high proportion of the magnesium in the earth will have separated at an early stage and the associated minerals of the magnesium-rich peridotitic rocks are usually refractory oxides like magnetite and chromite.

Apart from igneous rocks proper there are several other types which may contain considerable amounts of magnesium:

(1) Serpentinous and talcose rocks presumably derived from the weathering or sub-surface alteration by hydrothermal solutions of olivine rocks.

(2) Extreme alteration of such rocks by carbonated solutions giving rise to massive magnesite deposits which may be valuable as source minerals for magnesium.

(3) Replacement deposits where limestone rocks have been altered by action of magnesian solutions, possibly by the reaction

$$MgCl_2 + CaCO_3 = MgCO_3 + CaCl_2$$

This commonly results in the formation of dolomite $CaMg(CO_3)_2$.

This mineral, of which whole mountain masses are made, is not a solid solution series between calcite and magnesite. It is formed by the regular substitution of alternate ions of calcium and magnesium in the crystal lattice of calcite. The reason for this is the large difference in ionic radii between Mg (0.66 A) and Ca (0.99 A) which is unfavourable to diadochy. A great many limestones have suffered some degree of dolomitization which thereby reduces their value as sources of lime.

In aqueous media magnesium ions tend to acquire six water molecules and the comparative paucity of the element in soils is due to the lack of adsorbed ions - an effect also observed for the equally readily hydrated ions of sodium. The initially small cation becomes relatively large by hydration whereas the initially larger potassium ion generally remains non-hydrated and is therefore much more readily adsorbed on soil colloids.

The average concentration of magnesium in the earth's crust is approximately 20,900 ppm.

(17)

Manganese

(a) Mn concentration range in Ontario tailings areas (121 samples) ~10 - 2,870 ppm

(b) Average Mn concentration in Ontario tailings areas (121 samples) - 702 ppm

(c) Manganese Background Data

NOTE: Also see Section A of this report

In the earth's crust manganese comes eighth in order of abundance as far as metals are concerned and twelfth for the elements as a whole. The estimated abundance is 1000g/ton.

As a transitional element, manganese is well known for its multiplicity of oxidation states. As far as natural chemistry is concerned these are probably confined to 2, 3, and 4. The element is essentially cationic and the highly oxidized anions MnO_4^{2-} and MnO_4^- are unknown in nature. In general it may be said that Mn^{2+} ions are characteristic of igneous rocks, particularly the deep-seated types, whilst the sediments generally show a higher oxidation state, Mn^{4+} being characteristic. The Mn^{3+} ion seems to occur in only a limited number of minerals.

The ionic radius of manganese as Mn^{2+} is 0.80 A which is only slightly larger than Fe^{2+}, which is 0.74 A. Considerable interchange between the two ions in crystal lattices is therefore possible. The ions of calcium, magnesium, and several other metals also come fairly near to manganese in size and the element is therefore widely present in minerals, particularly silicates, as a trace or minor element. The ability of manganese to enter into silicate minerals causes it to be found in amounts approaching the average crustal abundance (1000 g/ton) in all types of igneous rocks. On the whole manganese does not become enriched at any particular stage of magmatic crystallization and there are no manganese ore bodies of magmatic type.

Independent manganese minerals are not usually found in igneous rocks; they are more characteristic of hydrothermal and metasomatic deposits.

Manganese can also form a few sulphide minerals. The monosulphide MnS is analogous to the sulphides of zinc and cadmium. The mineral MnS_2 does not seem to be fully analogous to pyrite FeS_2 - instead of being semi-metallic it may be fully ionic in structure.

Manganese-bearing minerals of primary origin predominantly contain the Mn^{2+} ion and, in the process of weathering, this passes into solution as $Mn(HCO_3)_2$. A few manganous compounds are found in hydrothermal veins. The stability of such compounds is probably related to their solubility (thus the tungstate minerals hübnerite

and wolfram are very stable) or more generally to the hydrogen ion concentration of their environment which has an important bearing on the oxidation potential required to convert Mn^{2+} to Mn^{3+} or Mn^{4+}. It is at this stage that there is a decided parting of the geochemical ways of manganese and iron. In the case of the Mn^{2+} ion the oxidation potential in acid solution is quite high at + 1.51 V at pH 4 and below and 0 V decreasing to less than - 0.4 V at pH values above 8. In the case of iron the potential required at pH 2.5 for Fe^{2+} to Fe^{3+} is only 0.77 V, and at pH 6 has fallen to only - 0.1 V. It is evident from this that ferrous ions are more readily oxidized than manganous ions and that the latter will tend to be stable over a wider range of pH, hence the Mn^{2+} ions from weathering processes remain mobile for greater distance than Fe^{2+} ions. The higher manganese hydroxides which are produced by oxidation are not stable but break down into the hydrated oxide $MnO_2.nH_2O$ and this substance separates as a negative colloid.

MANGANESE MINERALS

Name	Formula	Occurrence
Alabandite	MnS	Hydrothermal veins
Hauerite	MnS_2	Rare mineral in gypsum and sulphur deposits
Manganosite	MnO	In H.T. veins, etc.
Pyrochroite	$Mn(OH)_2$	Low temperature H.T. deposits
Hausmannite	Mn_3O_4	Bedded ore deposits
Psilomelane	$(Ba,H_2O)_2Mn_5O_{10}$	
Pyrolusite	MnO_2	
Manganite	$MnO.OH$	
Galaxite	$MnAl_2O_4$	H.T. deposits
Bixbyite	$(Mn,Fe)_2O_3$	Metamorphic ores
Scacchite	$MnCl_2$	Fumarolic deposits
Rhodonite	$MnSiO_3$	H.T. and Metasomatic minerals
Tephroite	Mn_2SiO_4	
Sussexite	$(Mn,Mg)_2B_2O_5H_2O$	
Rhodochrosite	$MnCO_3$	
Braunite	$Mn^{2+}Mn_6^{3+}SiO_{12}$	Bedded ore deposits
Alleghanyite	$Mn_5Si_2O_8(OH)_2$	
Glaucochroite	$(Mn,Ca)_2SiO_4$	
Pyroxmangite	$(Mn,Fe)SiO_3$	Metamorphic deposits
Spessartine	$Mn_3Al_2Si_3O_{12}$	
Pennantite	$Mn_9Al_6Si_5O_{20}(OH)_{16}$	

Name	Formula	Occurrence
Stewartite	$Mn_3(PO_4)_2 4H_2O$	Oxidized zones
Natrophilite	$NaMnPO_4$	of H.T. veins
Mallardite	$MnSO_4 7H_2O$	
Hübnerite	$MnWO_4$	H.T. veins

The manganese content of soils is variable in the range 200-5000 ppm and it is frequently concentrated in horizons rich in organic matter where it is presumably immobilized by complex formation.

Mercury

(a) Hg concentration range in Ontario tailings areas (121 samples) .005 - 2,350 ppm

(b) Average Hg concentration in Ontario tailings areas (118 samples) - .736 ppm

(c) Mercury Background Data

NOTE: Also see Section A of this report

MERCURY MINERALS

Name	Formula
Mercury	Hg
Amalgam	Ag,Hg
Cinnabar	HgS
Tiemannite	HgSe
Coloradoite	HgTe
Livingstonite	$HgSb_4S_7$
Montroydite	HgO
Calomel	Hg_2Cl_2

Seven stable isotopes of mercury exist in nature:

^{196}Hg = 0.146%	^{201}Hg = 13.22%
^{198}Hg = 10.02%	^{202}Hg = 29.80%
^{199}Hg = 16.84%	^{204}Hg = 6.85%
^{200}Hg = 23.13%	

There is no very certain information as to isotopic variations under natural conditions but with such a volatile element it is possible that fractionation by diffusion or distillation might well take place under suitable circumstances in the earth.

Abundance and Geochemistry

Mercury is relatively abundant for a heavy element but it must nevertheless be considered among the scarcer of the elements, the estimated value for the earth's crust of about 0.5 g/ton being about the same as that of silver. Mercury shows a much higher abundance in the sedimentary layers of the crust than it does in igneous rocks generally, and it seems certain that mercury has reached the surface layers by processes other than weathering. It would seem that the element is particularly mobile under magmatic and hydrothermal conditions. According to Goldschmidt, mercury compounds in magmas would in general be reduced to the metal by ferrous ions. The highly volatile metal would then pass readily upwards where at a later stage it would be mainly fixed by combination with sulphur.

Concentrations of mercury in nature are extremely few but they may nevertheless be very rich. It seems probable that very special conditions are necessary in order to immobilize mercury in the form of its usual sulphide ore. It has been suggested that silica may act as a precipitant on alkaline solutions of sulpho-salts of mercury and the presence of bituminous material has also been postulated as a reducing and sulphurizing agent.

The actual formation of mercury minerals from thermal waters in volcanic regions of California has been observed. It is also probable that a mercury deposit once formed may be rather easily removed again by hydrothermal and weathering processes.

In the study of metallic and semi-metallic compounds, the radii in the metallic state, in 12-coordination, form a most useful basis for comparisons. These radii can be found from atomic distances in pure metals or in alloys, the standard state being the face-centred cubic close-packed structure. For 'tetrahedral' sulphides and 'tetrahedral' sulphosalts the old 'atomic' radii from such compounds, or, as they are now named, tetrahedral covalent radii, are useful. The standard states are the diamond structure of elements and the sphalerite structure of binary compounds. An excellent table of these radii has been given by L. Pauling (1942). The ionic radii are useful for all compounds which, wholly or in part, have ionic bonds, but we may use them for covalent compounds with certain reservations. They can in many cases be usefully applied to the cations of simple sulphides and typical sulpho-salts.

The following table gives a comparison between mercury and some geochemically related metals using these three sets of radii. The metallic radius of mercury has been determined from an alloy, the ionic radius from the ionic compound HgF_2, and the tetrahedral radius from tetrahedral HgS (metacinnabar).

				Å			
Element	Zn	Ag	Cd	Hg	Tl	Pb	Bi
Metallic	1.37	1.44	1.52	1.55	1.71	1.74	1.82
Tetrahedral	1.31	1.53	1.48	1.48	1.47	1.46	1.46
Ionic Charge	2+	1+	2+	2+	1+	2+	3+
Ionic Radius	0.83	1.13	1.03	1.12	1.49	1.32	1.1

The remarkable similarity between mercury and cadmium is immediately noticeable, whatever radius is used for the comparison. This is due to the lanthanide contraction which almost completely compensates for the increase in dimensions which would otherwise result from the completion of the 5d electron level in mercury as compared with the 4d in cadmium. It is likely therefore that the geochemistry of mercury will, in many respects, by analogous to that of cadmium, excepting such differences as must result from the difference in ionization energy of the elements and the free energy of formation of their compounds.

We should therefore expect mercury to enter sphalerite and other 'tetrahedral' minerals, such as tetrahedrite and chalcopyrite, in the same manner as cadmium. Further, we may expect mercury to be able to enter galena and, for instance, the various sulpho-antimonides of lead. Perhaps the most interesting problem, however, is that it is quite conceivable that mercury ions may be 'captured' in sulphides, selenides, and tellurides, and especially in sulpho-salts, of univalent silver, which has a size not unlike that of divalent mercury. Thus, the occurrence of mercury might be expected in very many of these minerals.

Mercury ions could only enter rock-forming silicates in magmatic silicates under a pressure high enough to prevent subsequent evaporation of metallic mercury or of volatile mercury compounds. If such ionic substitution really takes place, which is still unknown, the entry of mercury would be possible in calcium minerals, perhaps in apatite.

Mercury in Magmatic Rocks

The few data available indicate that mercury, like cadmium, is concentrated preferentially in gabbroid magmas. A. Stock and F. Cucuel (1934) found about 0.08 ppm Hg in gabbros and 0.06 ppm in granites. In a basalt from the Kaiserstuhl in southern Germany they found 0.10 ppm Hg. According to data at present available the occurrence of mercury minerals in hydrothermal veins is connected mainly with basaltic or andesitic volcanic activity.

Besides the sulphide and the rare selenide and telluride, the metal and the various amalgams, mercury in hydrothermal deposits is also found as a substituent in sulphur compounds of other minerals, e.g. the 'tetrahedral' minerals, tetrahedrite and sphalerite. In tetrahedrite especially substantial percentages of mercury have been encountered. In non-tetrahedral minerals of silver and lead, such as argyrodite, clausthalite, and altaite, mercury has also been reported. Mercury certainly will also be found in greenockite, the sulphide of cadmium.

Concerning the occurrence of mercury in sphalerite, a number of data have been given by I. Oftedal (1941), who reports up to 1,000 ppm Hg in sphalerites from deposits formed at low hydrothermal temperatures or in cementation zones, and from 10 to 100 ppm Hg in sphalerites from deposits formed at medium hydrothermal temperatures. No mercury (at any rate less than 10 ppm) has been observed in sphalerites from pegmatites or pyro-metasomatic deposits. Therefore, the same rule seems to hold for mercury as for cadmium, that the highest amounts are found in

deposits formed at low temperatures. Among the high-temperature hydrothermal sphalerites relatively high amounts, 10-100 ppm Hg, have been regularly observed in specimens from the pyrite-chalcopyrite deposits in Norway, which are very closely related to Caledonian gabbroid rocks and provide evidence of the association of mercury with gabbroid magmas.

Residual sediments must be assumed to be essentially free from mercury, except, of course, in cases of secondary mineralization by impregnation or by metasomatism. In fact, quartzites seem to be especially unfavourable for secondary collection of hydrothermal mercury ores, as in the case of the Palaeozoic quartzites of Almaden in Spain.

The bulk of the mercury in the sedimentary sequence without doubt collects in the marine hydrolysate sediments. In a composite sample of thirty-six European Palaeozoic marine shales from the Gottingen laboratory A. Stock found 0.5 ppm Hg. In later analyses of other shales he found from 0.025 to 1.4 ppm Hg, and and average of 0.5 ppm for hydrolysate sediments might agree with our present knowledge.

Molybdenum

(a) Mo concentration range in Ontario tailings areas (121 samples) 0.6 - 3,416 ppm

(b) Average Mo concentration in Ontario tailings areas (121 samples) - 1.35 ppm

(c) Molybdenum Background Data

NOTE: Also see Section A of this report

There are seven stable isotopes of this element in nature:

^{92}Mo = 15.86% ^{97}Mo = 9.45%
^{94}Mo = 9.12% ^{98}Mo = 23.75%
^{95}Mo = 15.70% ^{100}Mo = 9.62%
^{96}Mo = 16.50%

MOLYBDENUM MINERALS

Name	Formula	Occurrence
Molybdenite	MoS_2	High-temperature veins, etc., associated with granitic rocks
Molybdite	MoO_3 ?	Oxidized zones of mineral veins associated with granitic rocks
Lindgrenite	$Cu_3(MoO_4)_2(OH)_2$	
Powellite	$CaMoO_4$	
Wulfenite	$PbMoO_4$	
Koechlinite	$(BiO)_2MoO_4$	
Ferrimolybdite	$Fe(MoO_4)_3 \cdot 7\frac{1}{2}H_2O$	

Molybdenum is not a very abundant element terrestrially at 1 g/ton in the crust. Meteorite analyses show appreciable concentration of the element in the metallic and somewhat less in the sulphide phase, which would imply a siderophile and thiophile character for the element. In the earth's crust however, molybdenum is to be regarded as lithophile, being mainly associated with the later stages of magmatic crystalliz ation, viz., in granitic rocks. It is not, however, oxyphile as its principal natural compound is the disulphide molybdenite. This mineral has a characteristic layered lattice structure and is one of the few solid substances possessing lubricating properties.

The few oxygen compounds of molybdenum are rare and local. Its geochemistry shows some marked contrasts from that of its related element, tungsten. The free energy of formation of MoS_2 is almost 20% greater than that of WS_2, hence the greater stability of the former. On the other hand in respect of the oxides MoO_3 and WO_3 the positions are reversed.

Molybdenite is, as noted above, almost always found associated with the acidic (granitic) rocks as one of the later products of crystallization, occurring chiefly in pneumatolytic and high-temperature hydrothermal veins, etc. In consequence of this some economically valuable concentrations of the element are available. Oxidation to the oxide MoO_3 presumably occurs in zones of weathering but the composition of the mineral molybdite is somewhat doubtful.

It is evident that the MoO_4^{2-} ion is produced under these conditions and is initially in solution but is very readily immobilized in the form of sparingly soluble molybdates of various metals. Poly-molybdates do not seem to occur in nature. There are some rare cases of silicates of the feldspathoid group containing small percentages of molybdenum, but whether the MoO_4^{2-} ion replaces the SiO_4^{4-} ion, or whether, as in the case of sodalite, some of the chloride ions are replaced, is not yet certain. The behaviour of molybdenum in weathering processes is rather obscure; it appears, however, to be dissolved and may frequently be accumulated in oxidate sediments, particularly those containing manganese. The black bottom muds also show some concentration of molybdenum as MoS_2 and shales derived from them may contain some hundreds of parts per million of Mo. It has been established that molybdenum is an essential trace element for plants and probably enters into some of the organic complexes which function as coenzymes.

(20)

Nickel

(a) Ni concentration range in Ontario tailings areas (121 samples) - 10 - 10,000 ppm

(b) Average Ni concentration in Ontario tailings areas (114 samples) - 214 ppm

(c) Nickel Background Data

NOTE: Also see Section A of this report

There are five stable isotopes of this element in nature:

$^{58}Ni = 67.76\%$ $^{62}Ni = 3.66\%$

$^{60}Ni = 26.16\%$ $^{64}Ni = 1.16\%$

$^{61}Ni = 1.25\%$

With a crustal abundance of 80 g/ton, nickel is considerably more abundant than cobalt. It is a siderophile element and the estimated abundance for the earth as a whole is 2.7% (27,000 g/ton).

Nickel occurs very markedly in sulphides and is associated with the earlier products of magmatic crystallization, viz., the ultrabasic rocks. The nickel content of igneous rocks decreases progressively with increasing silica content, as shown below:

	Dunites	Gabbros	Diorites	Granites
Ni (ppm)	1500	150	30	9
SiO_2 (%)	40	48	57	70

Probably most of the nickel is contained in sulphide accessory minerals such as pyrrhotite. Some nickel minerals are found in hydrothermal deposits and it shows marked resemblance to copper in this respect. Valuable concentrations of nickel are, however, very local.

Nickel minerals are fairly numerous and there are some hydrous silicate minerals analogous to serpentine, chlorite, and montmorillonite. In weathering processes the Ni^{2+} ion is stable and not prone to oxidation like Fe^{2+} and Co^{2+}. Nickel is largely retained in minerals of the above types and lateritic weathering of serpentine rocks may cause considerable enrichment in nickel.

NICKEL MINERALS

Name	Formula
Millerite	NiS
Heazlewoodite	Ni_3S_2
Polydymite	Ni_3S_4
Vaesite	NiS_2
Niccolite	$NiAs$
Chloanthite	$NiAs_2$
Gersdorffite	$NiAsS$
Pentlandite	$(Fe,Ni)_9S_8$
Bravoite	$(Ni,Fe)S_2$
Bunsenite	NiO
Zaratite	$Ni_3CO_3(OH)_4{}^4H_2O$
Garnierite	$(Ni,Mg)_3Si_2O_5(OH)_4$
Annabergite	$Ni_3(AsO_4)_2{}^8H_2O$
Morenosite	$NiSO_4{}^7H_2O$

(21)

Nitrogen

(a) N concentration range in Ontario tailings areas (121 samples) 2.8 - 373 ppm

(b) Average N concentration in Ontario tailings areas (121 samples) - 58 ppm

(c) Nitrogen Background Data

NOTE: Also see Section A of this report

NITRATE MINERALS

Name	Formula
Nitratine	$NaNO_3$
Nitre	KNO_3
Gerhardtite	$Cu_2NO_3(OH)_3$
Nitromagnesite	$Mg(NO_3)_2 6H_2O$
Nitrocalcite	$Ca(NO_3)_2 nH_2O$
Nitrobarite	$Ba(NO_3)_2$
Buttgenbachite	$Cu_{19}Cl_4(NO_3)_2(OH)_{32} 3H_2O$
Darapskite	$Na_3NO_3SO_4H_2O$

(22)

Phosphorus

(a) P concentration range in Ontario tailings areas (121 samples) 38 - 12,300 ppm

(b) Average P concentration in Ontario tailings areas (118 samples) - 736 ppm

(c) Phosphorus Background Data

NOTE: Also see Section A of this report

Only the single nuclide ^{31}P occurs in nature.

The analysis of different phases of meteorites give no very conclusive indication of the geochemical affinities of the element. The most interesting aspect is its occurrence in the metallic and sulphide phases of meteorites as the phosphide schreibersite $(Fe,Ni,Co)_3P$. This seems to be the only case in nature of the definite occurrence of phosphorus in such a low oxidation state. The oxygen-rich conditions of the earth's crust lead, as far as is known, to the exclusive existence of phosphorus as the PO_4 ion. On account of the stability of this tetrahedral structure it presents analogies with the corresponding SiO_4 ion. It is in fact possible in a few cases for replacement of silicate by phosphate to take place. This only seems to happen among ortho-silicates like zircon $ZrSiO_4$, and the electrical neutrality of the lattice is then maintained by replacement of part of the tetravalent zirconium by trivalent lanthanide metals.

It is perhaps for this reason that such examples are not very common. An important difference from silicates is that the PO_4 tetrahedra in minerals apparently cannot link together by sharing oxygen atoms. The mineral chemistry of phosphorus is therefore less complex than that of silicon. There is also some analogy between PO_4 and SO_4 as is evident from the existence of a number of complex minerals containing both of these ions, which along with the silicate ion are all of about the same size, the X-O separation in these structures being generally 1.5 - 1.6 A. In practice phosphorus is to be regarded as a lithophile and oxyphile element. A large number of phosphates are known but it is probable that as much as 95% of the phosphorus of the earth's crust is contained in minerals of the apatite group. These are very common accessory minerals in igneous rocks. The general formula of apatites is $Ca_5(PO_4)_3X$, where X is an anion such as F, Cl, or OH. The commonest form is probably $Ca_5(PO_4)_3F$ or fluorapatite. The crystal lattice of this mineral is rather complex, involving a hexagonal network and arrangement of Ca and F ions which gives a very stable structure and allows of a remarkable amount of substitution of both cations and anions.

The phosphorus content of igneous rocks is generally well known and ranges from about 2000 g/ton for basic rocks like gabbro and basalt to 600 g/ton for acid rocks like granite and rhyolite. It is evident that a considerable proportion of the phosphorus crystallizes from the magma as an independent mineral and at a fairly early stage.

It was at one time thought that much of the apatite associated with basic, gabbroic rocks was chloroapatite, whilst the apatite of acidic, granitic rocks was mainly fluoroapatite, but this view is not now maintained. The OH content of apatites may be considerable. Apatite is also met with in hydrothermal veins to a minor extent, and it may occur as a detrital mineral in sedimentary rocks.

PHOSPHATE MINERALS

Name	Formula	Occurrence
Monetite	$CaHPO_4$	Underlying guano deposits
Alluaudite	$(Na,Fe,Mn)PO_4$	Altered pegmatites
Whitlockite	$Ca_3(PO_4)_2$	Pegmatites and phosphate deposits
Xenotime	YPO_4	Minor accessory
Monazite	$(Ce, etc.)PO_4$	rock minerals
Belinite	$AlPO_4$	Associated with certain iron ores
Brushite	$CaHPO_4 2H_2O$	Organic phosphates and cave earths
Vivianite	$Fe_3(PO_4)_2 8H_2O$	Altered ores, fossils
Cornetite	$Cu_3PO_4(OH)_3$	Oxidized
Pseudomalachite	$Cu_5(PO_4)_2(OH)_4 H_2O$	copper ores
Fluorapatite	$Ca_5(PO_4)_3F$	Accessory
Chlorapatite	$Ca_5(PO_4)_3Cl$	rock minerals
Hydroxyapatite	$Ca_5(PO_4)_3OH$	Organic phosphate residues
Pyromorphite	$Pb_5(PO_4)_3Cl$	Oxidized lead ores
Lazulite	$(Mg,Fe)Al_2(PO_4)_2(OH)_2$	Metamorphic aluminous, rocks
Turquoise	$CuAl_6(PO_4)_4(OH)_8 5H_2O$ ..	Secondary minerals
Wavellite	$Al_6(PO_4)_4(OH)_6 9H_2O$	

There are some features in the structure of fluorapatite which are of great importance for the understanding of the fixation of apatite in different milieus and for the conditions under which diadochic or isomorphous substitution in the apatite molecule can take place. A brief discussion of the atomic arrangement in the structure may therefore be useful.

The Ca^{2+} ions occur in two different positions. In the first case Ca-O columns are linked by PO_4 groups forming a hexagonal network with channels extending right through the structure in the c-direction. In this network the Ca ions are in ninefold coordination with oxygen, but owing to the sharing of oxygens with PO_4 groups the Ca:O ration is only 1:6.

The atomic arrangement in the channels is such that the walls are lined with oxygen atoms making six 'caves' per unit length in the wall of each channel. Ca ions (1.06 A) will fust fit into the caves, one Ca going about half way into each. Thus about half the area of each Ca is left exposed on the inside of the channels and the F atoms just fit between the group of three Ca ions at one level. In this second position Ca is in sevenfold coordination and surrounded by 6O + 1F.

The hexagonal network and the arrangement of Ca and F atoms in the channels give a very stable structure to fluorapatite. Since the size of $(OH)^-$ (1.4-1.6 A) is greater than that of F^- (1.33 A) the sturcture of hydroxyapatite is a little expanded compared with that of fluorapatite. The critical fit of F or OH evidently accounts for the difference in stability of the two members of the apatite group and, in fact, hydroxyapatite becomes transformed to fluorapatite even in environments very poor in fluorine.

The very stable structure of apatite permits rather unusual types of substitution. Thus calcium is replaced by sodium, potassium, manganese, strontium, magnesium, and carbon. Phosphorus is replaced by sulphur, silicon, arsenic, vanadium, and carbon. Fluorine is replaced by chlorine, oxygen(?), and hydroxyl but not by CO_3 groups. Oxygen, finally, is replaced by fluorine and hydroxyl.

These substitutions are found in several mineral species belonging to the apatite group. Several other cations are reported in analyses of apatites, for example barium, chromium, aluminum, rare earth metals, etc. It is however, often questionable whether or not these ions can enter the apatite structure in significant amounts.

(23)

Potassium

(a) K concentration range in Ontario tailings areas (121 samples) 489 - 72,000 ppm

(b) Average K concentration in Ontario tailings areas (121 samples) - 14,815 ppm

(c) Potassium Background Data

NOTE: Also see Section A of this report

POTASSIUM MINERALS

Name	Formula
Sylvite	KCl
Erythrosiderite	$K_2FeCl_5H_2O$
Hieratite	K_2SiF_6
Fairchildite	$K_2Ca(CO_3)_2$
Nitre	KNO_3
Ferri-orthoclase	$KFeSi_3O_8$
Kalsilite	$KAlSiO_4$
Leucite	$KAlSi_2O_6$
Orthoclase Microcline	$KAlSi_3O_8$
Muscovite	$KAl_3Si_3O_{10}(OH)_2$
Phlogopite	$KMg_3AlSi_3O_{10}(OH)_2$
Glauconite	$K_{1\frac{1}{2}}(Fe,Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4$
Lepidomelane	$K_2(Fe,Fe,Mg)_{4-6}(Si,Al,Fe)_8O_{20}(OH)_4$
Biotite	$K_2(Mg,Fe,Al,Fe)_{4-6}(Si,Al)_8O_{20}(OH)_4$
Mercalite	$KHSO_4$
Kainite	$KMgSO_4Cl.3H_2O$

There are four main potassium minerals in magmatic rocks: (1) potash feldspar $KAlSi_3O_8$, in the two main varieties microcline and orthoclase; (2) the feldspathoid mineral leucite, $KAlSi_2O_6$, which is confined mainly to volcanic rocks and rarely seen in plutonics; (3) the mica minerals of the muscovite series, $K(AlSi_3O_{10})Al_2(OH,F)_2$, and biotite series, $K(AlSi_3O_{10})Mg_3(OH,F)_2$, in which the magnesium ions may be replaced to a greater or lesser extent by ferrous and ferric iron.

Muscovite is often called 'potash mica', but biotite micas are just as entitled to that name. If any popular names were desirable, one might use aluminous mica for muscovite, and ferromagnesian mica for the biotite group. In the latter different varieties are distinguished by the proportions of magnesium and iron (mostly ferrous, but also ferric).

The geochemistry of potassium in plutonic rocks depends upon the formation of two possible potassium minerals, anhydrous potash feldspar and biotite. The latter also contains as an essential constituent the univalent hydroxyl anion, which may be replaced by fluorine. The scarcity of fluorine in normal plutonic rocks limits the the formation of hydroxyl-free biotites, and the choice between the formation of potash feldspar and biotite in most cases depends on the water content of the magma.

(24)

Selenium

(a) Se concentration range in Ontario tailings areas (121 samples) 1 - 100 ppm

(b) Average Se concentration in Ontario tailings areas (116 samples) - 3.7 ppm

(c) Selenium Background Data

NOTE: Also see Section A of this report

The estimated crustal abundance of the element of less than 0.1 g/ton indicates that selenium is rather scarce . It is almost exclusively chalcophile, occurring in minerals where it replaces sulphur. The occurrence of the oxide SeO_2 as the mineral selenolite is somewhat doubtful. The selenites seem to be represented by a very few minerals of which only one need be mentioned, viz., chalcomenite $CuSeO_3 2H_2O$. Selenium requires a higher oxidation potential than sulphur to raise it to the hexavalent state and this is not often realized in nature - the mineral selenojarosite

$$KFe_3^{3+}((S,Se)O_4)(OH)_6$$

seems to be a rare example of genuine SeO_4 ions in a natural substance.

Other selenium minerals are indicated below:

SELENIUM MINERALS

Name	Formula
Selenium	Se
Klockmannite	CuSe
Berzelianite	Cu_2Se
Naumannite	Ag_2Se
Tiemannite	HgSe
Clausthalite	PbSe
Guanajuatite	$Bi_2(S,Se)_3$
Achavalite	FeSe
Crookesite	$(Cu,Tl,Ag)_2Se$
Penroseite	$(Ni,Cu)Se_2$

The elements sulphur and selenium are closely related crystallochemically and also in certain aspects of their geochemistry. The radii of S^{2-} (1.74 A) and of Se^{2-} (1.91 A) are so close that selenium can, and does, readily enter the lattices of sulphides. In addition selenium is commonly present in native sulphur of volcanic origin. On the other hand the great deposits of sulphur in sedimentary rocks are either free of selenium, e.g. those of Texas and Lousiana, or contain a very small amount, e.g. those of Sicily. In magmatic rocks probably all the selenium is in the sulphide minerals, and its presence in pyrite-chalcopyrite ores, which are genetically related to magmatic rocks, is well known from numerous analyses.

In the truly magmatic sulphides, viz. the pyrrhotite-pentlandite segregations of basic plutonic rocks, the ratio Se:S is 1:7,000. In shales the ratio is 1:4,000. A higher content of selenium relative to sulphur is found in a few pneumatolytic and high-hydrothermal sulphides and also in sedimentary oxidic iron ores; a lower Se content is found in most of the sulphide deposits of low-temperature hydrothermal and sedimentary origin, as well as pyrite-chalcopyrite deposits formerly held to be of magmatic origin. We can therefore take the average ratio of Se:S for magmatic rocks as 1:6,000, representing an average selenium content of 0.09 ppm.

Goldschmidt and Strock (1935) analysed a number of pyrrhotite-pentlandite ores and showed that the selenium content ranged from 17 to 57 ppm, which gave an S:Se ratio of 4,400 to 12,400 by weight. Genetically close to these ores is the eruptive troilite from the serpentine in Norte Co., California, which showed a selenium content of 32 ppm. Pyrrhotite nodules from the gabbro at Radau-Tals in the Harz contained 32 ppm Se. For the pyrite-chalcopyrite ores of probable magmatic origin they quoted results by St. Foslie who found that the weight ratio S:Se generally varied from 1,800 to 25,000, with an extreme case of 94,000, which may represent a deposit of sedimentary origin. The average value of the ratio of sulphur to selenium for these ores is between 10,000 and 20,000, distinctly higher than for the pyrrhotite-pentlandite ores.

The data on the pneumatolytic and hydrothermal sulphides can be considered in relation to the temperature of formation, i.e. pneumatolytic and high-temperature hydrothermal occurrences including contact rocks, mesothermal occurrences, and epithermal deposits. Among minerals belonging to the first group, molybdenite from Knaben, Norway, showed a content of 180 ppm Se, zinc blende from St. Agnes, Cornwall, contained 44 ppm, löllingite from Reichenstein giving similar values; pyrite from gangue quartz showed only 2.5 ppm Se. O. H. Odman (1941) in a study of quartz-tourmaline veins associated with basic lamprophyre dykes found that they were characterized by the presence of sulphosalts carrying large amounts of selenium. Cosalite ($CuPb_7Bi_8S_{22}$)

with 6.3% Se and kobellite ($Pb_2(Bi,Sb)_2S_5$) with 4.8 to 5.7% Se were identified. Of the mesothermal minerals examined by Goldschmidt concentrates of galena and zinc blende from Bad Grund contained 0.8 and 4 ppm respectively; a pyrite (with gold) from Gilpin Co., Colorado, contained 2 ppm. As examples of the low hydrothermal range a galena from Upper Silesia contained 2.3 ppm Se; zinc blende and marcasite from the same locality contained 2.4 and 1.8 ppm respectively

(25)

Sodium

(a) Na concentration range in Ontario tailings areas (121 samples) 693 - 68,900 ppm

(b) Average Na concentration in Ontario tailings areas (119 samples) - 13,871 ppm

(c) Sodium Background Data

NOTE: Also see Section A of this report

Sodium stands high among the elements with an abundance of 28,300 g/ton. It is present in all outer spheres of the earth.

Atmospheric sodium is one of the minor constituents of the upper atmosphere and is apparently present in the form of neutral sodium atoms to the extent of 10^4 atoms/cm^3 at a height of 70 km. It is believed that excitation of sodium atoms to the ^2P level is brought about by interactions involving atomic oxygen and is one of the causes of twilight and night luminescence of the sky.

In the hydrosphere sodium is the most abundant cation at 10,556 g/ton.

There are three main modes of occurrence of sodium compounds in the solid crust of the earth:

(a) In a limited number of complex aluminohalide minerals.
(b) In a very large number of complex silicate minerals, typically associated with igneous rocks. No simple silicate of sodium exists in nature.
(c) In a considerable variety of soluble salts, simple and complex, which are found mainly in deposits of the evaporite type.

SODIUM MINERALS

Name	Formula
Villiaumite	NaF
Halite	NaCl
Hydrohalite	$NaCl.2H_2O$
Cryolite	Na_3AlF_6
Chiolite	$Na_5Al_3F_{14}$
Malladrite	Na_2SiF_6
Ferruccite	$NaBF_4$
Borax	$Na_2B_4O_7.10H_2O$
Natron	$Na_2CO_3.10H_2O$
Trona	$Na_3H(CO_3)_2.2H_2O$
Gay-Lussite	$Na_2Ca(CO_3)_2.5H_2O$
Burkeite	$Na_6SO_4(CO_3)_2$
Nitratine	$NaNo_3$
Darapskite	$Na_3NO_3SO_4H_2O$

Name	Formula
Pectolite	$NaCa_2Si_3O_8OH$
Soda-tremolite	$Na_2CaMg_5Si_8O_{22}(OH)_2$
Riebeckite	$Na_2Fe_3^{\cdot\cdot}Fe_2^{\cdot\cdot\cdot}Si_8O_{22}(OH)_2$
Aegirine	$NaFe^{\cdot\cdot\cdot}Si_2O_6$
Iron-albite	$NaFe^{\cdot\cdot\cdot}Si_3O_8$
Nepheline	$NaAlSiO_4$
Albite	$NaAlSi_3O_8$
Jadeite	$NaAlSi_2O_6$
Natrolite	$Na_2Al_2Si_3O_{10}2H_2O$
Analcime	$NaAlSi_2O_6H_2O$
Anorthoclase	$(Na,K)AlSi_3O_8$
Stilbite	$NaCa_2Al_5Si_{13}O_{36}14H_2O$
Stercorite	$NH_4NaHPO_4H_2O$
Matteucite	$NaHSO_4H_2O$
Thenardite	Na_2SO_4
Mirabilite	$Na_2SO_410H_2O$
Aphthitalite	$NaKSO_4$
Krönkite	$Na_2Cu(SO_4)_22H_2O$
Vanthoffite	$Na_6Mg(SO_4)_4$
Loeweite	$Na_2Mg(SO_4)_22\frac{1}{2}H_2O$
Natroalunite	$NaAl_3(SO_4)_2(OH)_6$
Schairerite	$Na_3SO_4(F,Cl)$
Sulphohalite	$Na_6(SO_4)_2ClF$

The sodium ion is rather widely separated in size from those of lithium (radius 0.68 A) and potassium (radius 1.33 A). In consequence sodium ions are less associated with those of potassium than a pure chemist would perhaps expect. The sodium ion (radius 0.98 A) is much nearer to that of calcium (radius 0.99 A) and is very frequently associated with it in the important silicate minerals of igneous rocks.

Furthermore the two elements are of nearly equal abundance in the earth and are often met with in series of solid solutions of isomorphous minerals. The most important example is provided by the feldspars - characteristic and often dominant minerals of the igneous rocks of the intermediate and upper zones of the crust. The three simple types are orthoclase $KAlSi_3O_8$, albite $NaAlSi_3O_8$, and anorthite $CaAl_2Si_2O_8$.

The plagioclase feldspars are an isomorphous series between albite and anorthite and are very common particularly in basic and intermediate rock types.

As complete solid solution between soda and potash feldspars only exists above 660° C, the mineral anorthoclase $(Na,K)AlSi_3O_8$ is relatively rare and is often replaced by a micro-intergrowth of albite and orthoclase called perthite.

Another solid solution series exists between diopside $CaMgSi_2O_6$ and aegirine $NaFeSi_2O_6$, and there are also variable amounts of sodium in the hornblendes

$$NaCa_2(Mg, Fe, Al)_5(Si, Al)_8O_{22}(OH)_2.$$

The so-called alkaline rocks contain the feldspathoid minerals such as nepheline $NaAlSiO_4$ and sodalite $Na_8(AlSiO_4)_6Cl_2$, and also account for large amounts of sodium in the earth's crust. There are large tracts of alkaline rocks - e.g., in South Norway where sodium predominates over potassium. Among minerals of secondary origin which contain sodium the most important are the zeolites. As these minerals possess cationic exchange properties it is not uncommon to find sodium replacing calcium in several of the species which are not primarily sodium compounds. It is of interest that sodium is on the whole absent from some groups of silicates such as the micas, which, however, contain potassium and sometimes lithium.

The typical minerals of sedimentary rocks are devoid of sodium because in weathering the sodium passes into solution and there is no natural process by which it can be rendered insoluble and immobilized. Thus Goldschmidt was able to show that the estimated amount of sodium extracted by weathering from the primary rocks could be largely accounted for in the sodium content of ocean water. There is not much tendency for sodium ions to be adsorbed by colloidal sedimentary material and the small Na^+ content of marine muds and shales is mainly due to minute grains of unaltered albite.

(26)

Strontium

(a) Sr concentration range in Ontario tailings areas (121 samples) 5 - 439 ppm

(b) Average Sr concentration in Ontario tailings areas (121 samples) - 96 ppm

(c) Strontium Background Data

NOTE: Also see Section A of this report

For the earth's crust the strontium content is estimated at 450 g/ton whence it is eighty times as scarce as calcium but only 12% more abundant than barium. The number of independent strontium minerals is relatively small.

The peculiarities of the geochemistry of strontium are very largely related to the size of its ion compared with those of calcium, barium, and to a lesser extent potassium:

Ca^{2+} = 0.99 A, Sr^{2+} = 1.12 A, K^{+} = 1.33 A, Ba^{2+} = 1.34 A

On account of the rather low abundance of strontium it tends to be a guest ion in both magmatic and aqueous conditions.

The strontium ion is 13% larger than the calcium ion and 16% smaller than the barium or potassium ions. There is therefore about equal tendency for strontium ions to enter calcium minerals or barium minerals but, on account of the greater abundance of the former, strontium is more often found in small amounts in calcium minerals.

Barium can replace potassium to a greater extent than strontium, with its smaller ion, is able to do. The general position is that strontium is frequently found in the calcium minerals of the alkalic types of igneous rocks and also in the basic types but to a much smaller extent in the silicates of granitic rocks.

There is a marked deficiency of strontium in the complex silicates which contain calcium with magnesium and ferrous iron, and only rarely is it found in potash feldspars. There is a small tendency for strontium to accumulate in magmatic residua and therefore discrete deposits of strontium minerals are sometimes found in hydrothermal veins. The mineral celestite, however, is mainly found in bedded deposits with gypsum and sometimes sulphur.

STRONTIUM MINERALS

Name	Formula	Occurrence
Veatchite	$Sr_3B_{16}O_{27}{}^{5H_2O}$	Veins in limestone
Strontianite	$SrCO_3$	hydrothermal veins
Strontium-heulandite	$(Na,Ca,Sr)_4Al_6(Al,Si)_4Si_{26}O_{72}{}^{2H_2O}$	Zeolitic
Brewsterite	$(Sr,Ba)Al_2Si_6O_{16}{}^{5H_2O}$	Zeolitic
Goyazite	$SrAl_3P_2O_7(OH)_7$	Pegmatites
Svanbergite	$SrAl_3PO_4SO_4(OH)_6$	Metamorphic minerals
Celestite	$SrSO_4$	Bedded deposits with gypsum

(27)

Sulphur

(a) S concentration range in Ontario tailings areas (121 samples) 921 - 106,144 ppm

(b) Average S concentration in Ontario tailings areas (121 samples) - 14,724 ppm

(c) Sulphur Background Data

NOTE: Also see Section A of this report

There are four stable isotopes of sulphur in nature:

^{32}S = 95.1% ^{34}S = 4.2%

^{33}S = 0.74% ^{36}S = 0.016%

Sulphur is quite an abundant element in the earth's crust at 520 g/ton but is probably more abundant in the earth as a whole, the amount according to Mason, being 2.7%.

(28)

Tin

(a) Sn concentration range in Ontario tailings areas (121 samples) 3 - 336 ppm

(b) Average Sn concentration in Ontario tailings areas (121 samples) - 105 ppm

(c) Tin Background Data

NOTE: Also see Section A of this report

There are ten stable isotopes of tin in nature, which is a greater number than for any other element:

^{112}Sn = 0.95%	^{118}Sn = 24.01%
^{114}Sn = 0.65%	^{119}Sn = 8.58%
^{115}Sn = 0.34%	^{120}Sn = 32.97%
^{116}Sn = 14.24%	^{122}Sn = 4.71%
^{117}Sn = 7.57%	^{124}Sn = 5.98%

Tin is a relatively rare element in the earth's crust, the abundance being estimated at 3 g/ton.

In contrast with lead, tin does not form very many independent minerals. Some tin (which is present more particularly in acidic rocks), may be concealed in such silicate minerals as sphene $CaTiSiO_5$. The much larger ionic radius (Sn^{4+} = 0.71 A) is not favourable to the replacement of silicon by tin in common silicate minerals but it might be able to replace Ti^{4+}.

The occurrence of native tin appears to be rather doubtful as also is the occurrence of the sulphide SnS herzenbergite.

TIN MINERALS

Name	Formula	Occurrence
Stannite	Cu_2SnFeS_4	Hydrothermal veins, Cornwall, etc.
Teallite	$PbSnS_2$	
Montesite	$PbSn_4S_5$	Silver-tin veins,
Cylindrite	$Pb_3Sn_4Sb_2S_{14}$?	Bolivia
Franckeite	$Pb_5Sn_3Sb_2S_{14}$?	
Cassiterite	SnO_2	Hydrothermal & pneumatolytic deposits, widespread
Nordenskiöldine	$CaSnB_2O_6$	South Norway
Stokesite	$CaSnSi_3O_9 2H_2O$	S. W. Africa
Arandisite	$Sn_5Si_3O_{16} 4H_2O$	

Titanium

(a) Ti concentration range in Ontario tailings areas (121 samples) 10 - 2,650 ppm

(b) Average Ti concentration in Ontario tailings areas (121 samples) 645 ppm

(c) Titanium Background Data

NOTE: Also see Section A of this report

There are five stable isotopes of this element in nature:

^{46}Ti = 7.95% ^{49}Ti = 5.51%

^{47}Ti = 7.75% ^{50}Ti = 5.34%

^{48}Ti = 73.45%

Titanium is very markedly lithophile in character. It occurs frequently in the form of oxide minerals, some of which tend to separate from a cooling magma at a fairly early stage. A limited number of independent titanium minerals are known and titanium is concealed in small quantities in many rock minerals. It appears that the commonest mineral, ilmenite, is a compound oxide in which the structure is as hematite Fe_2O_3, but with every other iron atom replaced by one of titanium.

Goldschmidt, however, considered ilmenite to be a titanate of ferrous iron $Fe^{2+}Ti^{4+}O_3$. The determination of the valency of titanium in its minerals presents difficulties. In the mineral perovskite the structure is also that of a complex oxide. In sphene we have a calcium titanyl orthosilicate $CaTiO(SiO_4)$. It seems unlikely that titanium anions occur in nature.

TITANIUM MINERALS

Name	Formula	Occurrence
Rutile Anatase Brookite	TiO_2	Accessory minerals in igneous & metamorphic rocks & cavities & veins in the same
Perovskite Ilmenite Sphene	$CaTiO_3$ $FeTiO_3$ $CaTiSiO_5$	Accessory minerals in igneous rocks, also in dykes and pegmatites. May be residual in sands
Pyrophanite Benitoite Leucosphenite	$MnTiO_3$ $BaTiSi_3O_9$ $Na_3CaBaBTi_3Si_9O_{29}$	Rare rock minerals

The average concentration of titanium in the earth's crust is reported to be 4,400 ppm.

(31)

Vanadium

(a) V concentration range in Ontario tailings areas (121 samples) 22 - 1,350 ppm

(b) Average V concentration in Ontario tailings areas (121 samples) - 178 ppm

(c) Vanadium Background Data

NOTE: Also see Section A of this report

There are two stable isotopes of this element in nature:

$$^{50}V = 0.24\%$$
$$^{51}V = 99.76\%$$

The element, as observed above, is lithophile. It has a crustal abundance of 110 g/ton and cannot be regarded as a rare element. Vanadium is, however, rather widely dispersed and is mainly found as a fairly abundant trace element in rocks. It also forms a variety of independent minerals. These characters may be related to the existence in nature of at least three oxidation states, 5, 4, and 3, and the tendency to the formation of complexes with oxygen and sometimes with sulphur. The ionic radius of trivalent vanadium (0.65 A) is near to that of ferric iron (0.67 A) so that there is some degree of replacement in iron minerals, particularly in the magnetite Fe_3O_4 associated with gabbroic magmas, which may contain 2,000 ppm. The vanadium content of the more siliceous diorites and granites is appreciably lower. To a limited extent the vanadium in igneous rocks may occur as the VO_4 ion, as a replacement in silicate minerals. Vanadium is not commonly present in hydrothermal deposits except occasionally as in the form of secondary minerals of oxidized zones - e.g., vanadinite.

VANADIUM MINERALS

Name	Formula	Occurrence
Patronite	VS_4	In bituminous veins
Navajoite	$(V_2O_5).3H_2O$	
Montroseite	$(V,Fe)O.OH$	
Vanoxite	$(VO)_4V_2O_9.8H_2O$?	
Ardennite	$Mn_5Al_5(As,VO_4Si_5O_{20}(OH)_2.2H_2O$	Hydrothermal veins
Turanite	$Cu_5(VO_4)_2(OH)_4$	Sec. mineral in limestones
Tangeite	$CuCaVO_4(OH)$	Sec. mineral in sandstones
Pintadoite	$Ca_2V_2O_7.9H_2O$	
Steigerite	$AlVO_4.3\frac{1}{4}H_2O$	
Carnotite	$K_2(UO_2)_2(VO_4)_2.3H_2O$	

Name	Formula	Occurrence
Vanadinite	$Pb_5(VO_4)_3Cl$	Oxidized lead deposits
Roscoelite	Muscovite with V^{3+} replacing Al^{3+}	Rock mineral
Descloizite	$(Zn,Cu)Pb(VO_4)(OH)$	Oxidized zone of ore deposits
Mottramite	$(Cu,Zn)Pb(VO_4)(OH)$	
Pucherite	$BiVO_4$	

(31)

Zinc

(a) Zn concentration range in Ontario tailings areas (121 samples) <10 - 46,300 ppm

(b) Average Zn concentration in Ontario tailings areas (112 samples) - 209 ppm

(c) Zinc Background Data

NOTE: Also see Section A of this report

There are five stable isotopes of zinc in nature:

^{64}Zn = 48.89% ^{68}Zn = 18.56%

^{66}Zn = 27.81% ^{70}Zn = 0.62%

^{67}Zn = 4.11%

The value of 65 g/ton for the abundance in the earth's crust means that zinc is a relatively rare element but it is rather more abundant than copper. The way in which zinc is distributed is related to its markedly thiophile character which leads to it being concentrated in the sulphide phase of magmas where these exist.

In the upper parts of the crust it shows some lithophile character and with an ionic radius of 0.74 A it can enter lattices in place of Fe^{2+} (0.74 A), Mg (0.66 A) and several other similar ions. It therefore behaves as a trace element in some silicate minerals. Zinc is generally more abundant in basic and intermediate igneous rocks than in those of the acid type. It is readily involved in hydrothermal processes and therefore it is mainly found in concentrations in this type of deposit.

Zinc forms only one sulphide mineral of any consequence, but oxygen compounds, chiefly oxy-salts, are fairly numerous. Most of these are mainly of mineralogical interest, occurring in the oxidation zone of zinc deposits.

ZINC MINERALS

Name	Formula	Occurrence
Blende, sphalerite	ZnS	Hydrothermal veins
Heterolite	$ZnMn_2O_4$	Metamorphic Deposits
Gahnite	$ZnAl_2O_4$	
Franklinite	$(Zn,Mn,Fe^{2+})(Fe^{3+},Mn^{3+})_2O_4$	

Name	Formula	Occurrence
Roweite	$Ca(Mn,Mg,Zn)B_2O_5H_2O$	Oxidized zones of mineral veins
Smithsonite	$ZnCO_3$	
Hydrozincite	$Zn_5(CO_3)_2(OH)_6$	
Aurichalcite	$(Zn,Cu)_5(CO_3)_2(OH)_6$	
Willemite	Zn_2SiO_4	
Hemimorphite	$Zn_4Si_2O_7(OH)_2H_2O$	
Hardystonite	$Ca_2ZnSi_2O_7$	
Clinohedrite	$CaZnSiO_3(OH)_2$	
Larsenite	$PbZnSiO_4$	
Hopeite	$Zn_3(PO_4)_24H_2O$	
Scholzite	$Ca_3Zn(PO_4)_2(OH)_2H_2O$	
Köttigite	$Zn_3(AsO_4)_28H_2O$	
Goslarite	$ZnSO_47H_2O$	
Zincaluminite	$Zn_3Al_3SO_4(OH)_{13}2\frac{1}{2}H_2O$	

APPENDIX A

ANALYTICAL RESULTS

MINERAL TAILINGS

GOLD OPERATIONS

Analytical Results
Mineral Tailings
Gold Operations

PART A

TIMMINS AREA, ONTARIO

The analytical results quoted here are based on representative tailings samples taken at eleven Timmins area mining properties. These specific properties contain an aggregate total of over 106,000,000 tons of mineral tailings. There are several other large properties in the camp which were not sampled.

Sample Code	A	GG	JJ	LL
Production Commenced	1936	1915	1938	1940
Sodium as Na	16,200	3,490	1,780	6,650
Magnesium as Mg	14,100	11,300	19,100	19,000
Nitrogen as N	53.0	58.6	36.4	44.6
Fluorine as F	138	161	193	432
Aluminum as Al	37,000	27,900	11,800	16,000
Phosphorus as P	474	402	208	968
Chlorine as Cl	<10	42	17	17
Potassium as K	31,300	13,200	8,220	3,370
Calcium as Ca	7,970	6,080	7,720	6,150
Titanium as Ti	33	350	1,420	69
Vanadium as V	22	285	142	85
Chromium as Cr	149	169	257	308
Manganese as Mn	1,150	1,010	614	615
Iron as Fe	41,900	83,200	36,100	43,200
Cobalt as Co	14	39	17	34
Nickel as Ni	78	272	51	193
Copper as Cu	1,670	727	30	69
Zinc as Zn	2,150	179	79.2	39.7
Arsenic as As	428	588	426	8,600
Selenium as Se	<1	3	<1	<1
Strontium as Sr	177	30	31	36
Molybdenum as Mo	1.1	<0.6	<0.6	<0.6
Cadmium as Cd	13.4	1.5	0.9	1.2
Tin as Sn	96	67	58	84
Antimony as Sb	134	290	330	328
Boron as B	205	95	95	95
Barium as Ba	7	10	15	15
Mercury as Hg	1,730	.240	.096	.073
Lead as Pb	995	19	4	6
Bismuth as Bi	12	<10	<10	<10
Sulphate as SO_4	41,800	44,600	16,900	32,800
Carbonate as CO_3	<1,000	55,800	48,600	1,000

Sample Code	PP	QQ	RR	SS
Production Commenced	1937	1941	1939	1911
Sodium as Na	7,500	20,500	875	4,880
Magnesium as Mg	8,090	7,710	2,330	8,390
Nitrogen as N	8.4	80.6	27.8	64.1
Fluorine as F	167	169	306	264
Aluminum as Al	21,100	38,900	4,090	20,200
Phosphorus as P	136	780	261	473
Chlorine as Cl	17	33	17	25
Potassium as K	3,560	14,900	1,170	14,500
Calcium as Ca	2,710	4,240	486	4,100
Titanium as Ti	87	141	43	39
Vanadium as V	141	110	28	140
Chromium as Cr	197	106	39	78
Manganese as Mn	691	579	97	1,350
Iron as Fe	38,700	46,900	348,000	58,300
Cobalt as Co	14	19	74	30
Nickel as Ni	51	50	<10	<10
Copper as Cu	10	29	1,860	98
Zinc as Zn	69.1	154	4,070	351
Arsenic as As	790	1,220	1,310	820
Selenium as Se	3	8	5	<1
Strontium as Sr	20	81	25	52
Molybdenum as Mo	<0.6	<0.6	<0.6	<0.6
Cadmium as Cd	0.6	0.9	18.3	8.0
Tin as Sn	40	71	176	72
Antimony as Sb	368	332	625	374
Boron as B	77	92	82	84
Barium as Ba	5	14	15	15
Mercury as Hg	.314	.042	.017	.010
Lead as Pb	<1	8	3,160	70
Bismuth as Bi	19	<10	26	<10
Sulphate as SO_4	6,050	32,700	27,000	65,200
Carbonate as CO_3	<1,000	<1,000	<1,000	5,400

Sample Code	ZZ	Al	M13	R18
Production Commenced	1928	1926	1932	1938
Sodium as Na	2,820	8,300	3,450	4,490
Magnesium as Mg	10,100	13,400	5,320	11,500
Nitrogen as N	44.7	58.8	128	72.6
Fluorine as F	260	148	260	249
Aluminum as Al	16,400	16,200	9,360	29,100
Phosphorus as P	440	302	12,300	239
Chlorine as Cl	17	17	150	10
Potassium as K	9,530	4,340	2,660	19,300
Calcium as Ca	7,490	4,430	887	6,280
Titanium as Ti	84	43	175	837
Vanadium as V	195	161	56	399
Chromium as Cr	58	234	69	219
Manganese as Mn	1,410	670	<10	907
Iron as Fe	80,700	34,000	347,000	63,400
Cobalt as Co	47	13	187	25
Nickel as Ni	<10	<10	141	<10
Copper as Cu	175	19	1,230	120
Zinc as Zn	360	60.0	98.5	229
Arsenic as As	1,350	1,510	75,400	90
Selenium as Se	5	3	6	2
Strontium as Sr	46	30	21	31
Molybdenum as Mo	<0.6	<0.6	<0.6	0.6
Cadmium as Cd	1.5	0.6	3.8	0.3
Tin as Sn	119	70	171	63
Antimony as Sb	293	259	629	80
Boron as B	30	96	56	92
Barium as Ba	29	5	15	25
Mercury as Hg	<.005	<.005	.978	.153
Lead as Pb	45	32	23	15
Bismuth as Bi	<10	26	<10	<10
Sulphate as SO_4	114,000	20,700	95,500	25,200
Carbonate as CO_3	7,200	<1,000	<1,000	37,800

Sample Code	3B21	Data Range	Typical Composition
Production Commenced	1938	-	-
Sodium as Na	7,400	875 - 20,500	5,076
Magnesium as Mg	4,190	2,330 - 19,100	10,348
Nitrogen as N	78.0	8.4 - 128	62
Fluorine as F	236	138 - 432	230
Aluminum as Al	39,600	4,090 - 39,600	23,630
Phosphorus as P	890	136 - 12,300	464
Chlorine as Cl	30	<10 - 150	21
Potassium as K	36,500	1,170 - 36,500	12,504
Calcium as Ca	2,530	486 - 7,970	5,427
Titanium as Ti	30	30 - 1,420	100
Vanadium as V	156	22 - 399	148
Chromium as Cr	146	39 - 308	156
Manganese as Mn	516	<10 - 1,350	801
Iron as Fe	39,700	34,000 - 348,000	51,464
Cobalt as Co	24	13 - 187	28
Nickel as Ni	25	<10 - 272	70
Copper as Cu	88	10 - 1,860	low 71 high 1,371
Zinc as Zn	243	39.7 - 4,070	low 169 high 3,110
Arsenic as As	1,300	90 - 75,400	1,668
Selenium as Se	7	<1 - 8	3.5
Strontium as Sr	50	20 - 177	38
Molybdenum as Mo	<0.6	<0.6 - 1.1	<0.6
Cadmium as Cd	3.4	.3 - 18.3	4
Tin as Sn	74	40 - 176	89
Antimony as Sb	230	80 - 629	329
Boron as B	82	30 - 205	91
Barium as Ba	16	5 - 29	14
Mercury as Hg	.053	<.005 - 1.730	.166
Lead as Pb	51	<1 - 3,160	low 25 high 2,078
Bismuth as Bi	40	<10 - 40	<14
Sulphate as SO_4	22,500	6,050 - 114,000	38,627
Carbonate as CO_3	5,400	<1,000 - 55,800	low 2,500 high 47,400

PART B

KIRKLAND LAKE - LARDER LAKE AREA, ONTARIO

The following analytical results are based on representative tailings samples taken from 12 tailings areas located on 9 mining properties in the Kirkland Lake - Larder Lake gold area. These specific properties contain an aggregate total of over 75,800,000 tons of mineral tailings. There are other large properties in the camp which were not sampled.

Sample Code	Z26	F6	D4	HH
Production Commenced	1919	1921	1932	1939
Sodium as Na	14,000	23,000	18,400	11,700
Magnesium as Mg	8,970	4,920	5,940	13,600
Nitrogen as N	22.3	55.7	92.3	53.0
Fluorine as F	425	431	277	165
Aluminum as Al	29,500	45,200	39,100	10,900
Phosphorus as P	1,440	815	673	1,160
Chlorine as Cl	<10	17	17	25
Potassium as K	42,400	34,700	38,800	3,800
Calcium as Ca	3,840	2,700	2,780	3,700
Titanium as Ti	753	112	47	383
Vanadium as V	158	138	137	216
Chromium as Cr	157	87	182	293
Manganese as Mn	611	338	460	460
Iron as Fe	49,200	34,200	31,300	69,800
Cobalt as Co	35	27	13	59
Nickel as Ni	10	25	75	331
Copper as Cu	99	106	38	85
Zinc as Zn	108	77.1	105	104
Arsenic as As	39	116	115	6,920
Selenium as Se	2	10	<1	1
Strontium as Sr	295	263	232	34
Molybdenum as Mo	5.5	7.5	3.6	3.1
Cadmium as Cd	0.6	0.6	0.6	1.1
Tin as Sn	116	65	57	94
Antimony as Sb	212	79	234	271
Boron as B	100	76	79	92
Barium as Ba	25	10	14	<10
Mercury as Hg	.318	2.27	1.24	.068
Lead as Pb	9	26	18	<1
Bismuth as Bi	<10	<10	10	<10
Sulphate as SO_4	14,000	318,000	25,200	108,000
Carbonate as CO_3	3,600	5,400	5,400	23,400

Sample Code	Q17	P16	3B6	3B7
Production Commenced	1936	1936	1917	1917
Sodium as Na	14,800	24,400	17,600	1,490
Magnesium as Mg	8,360	4,100	8,770	1,190
Nitrogen as N	67.0	100	14.0	313
Fluorine as F	692	306	354	311
Aluminum as Al	38,800	30,000	33,800	11,100
Phosphorus as P	628	1,200	1,560	238
Chlorine as Cl	10	10	10	20
Potassium as K	55,100	8,590	38,100	9,210
Calcium as Ca	4,130	2,730	3,430	99.0
Titamium as Ti	805	93	787	216
Vanadium as V	315	312	114	119
Chromium as Cr	118	59	124	109
Manganese as Mn	1,370	937	648	<10
Iron as Fe	50,200	48,700	47,000	370,000
Cobalt as Co	22	47	13	463
Nickel as Ni	51	101	<10	386
Copper as Cu	236	29	76	1,820
Zinc as Zn	846	68.3	200	99.0
Arsenic as As	177	5,530	562	386
Selenium as Se	2	3	4	12
Strontium as Sr	439	63	391	52
Molybdenum as Mo	3.2	<0.6	1.6	55
Cadmium as Cd	2.7	0.6	0.6	51
Tin as Sn	81	68	123	308
Antimony as Sb	137	140	98	187
Boron as B	95	53	101	77
Barium as Ba	5	15	15	16
Mercury as Hg	.629	.171	3.76	9.46
Lead as Pb	89	<1	9	646
Bismuth as Bi	<10	<10	<10	14
Sulphate as SO_4	43,700	56,700	20,900	102,000
Carbonate as CO_3	19,800	<1,000	16,200	<1,000

Sample Code	V22	W23	X24	U21
Production Commenced	1918	1918	1918	1938
Sodium as Na	19,100	22,000	17,800	16,300
Magnesium as Mg	3,310	5,160	6,430	11,100
Nitrogen as N	47.5	61.2	66.8	83.4
Fluorine as F	362	233	273	218
Aluminum as Al	40,300	41,700	39,200	9,310
Phosphorus as P	716	776	1,030	514
Chlorine as Cl	10	10	90	190
Potassium as K	40,700	35,000	42,200	5,950
Calcium as Ca	1,690	2,630	3,170	4,890
Titanium as Ti	94	237	255	30
Vanadium as V	199	195	154	269
Chromium as Cr	159	107	144	566
Manganese as Mn	417	379	403	1,360
Iron as Fe	31,500	33,400	35,800	66,500
Cobalt as Co	16	14	11	37
Nickel as Ni	90	<10	<10	399
Copper as Cu	50	78	106	173
Zinc as Zn	119	87.5	76.8	355
Arsenic as As	80	117	77	825
Selenium as Se	2	<1	<1	4
Strontium as Sr	130	398	302	50
Molybdenum as Mo	4.4	4.3	6.4	3,416
Cadmium as Cd	0.3	0.6	0.3	0.9
Tin as Sn	52	93	102	75
Antimony as Sb	267	146	241	290
Boron as B	42	102	104	92
Barium as Ba	10	5	14	14
Mercury as Hg	2.44	.201	.007	.198
Lead as Pb	61	11	11	14
Bismuth as Bi	<10	<10	14	<10
Sulphate as SO_4	30,700	34,100	14,200	54,800
Carbonate as CO_3	5,400	5,400	3,600	73,800

Sample Code	Data Range	Typical Composition
Production Commenced	-	-
Sodium as Na	1,490 - 24,400	18,100
Magnesium as Mg	1,190 - 13,600	7,333
Nitrogen as N	14.0 - 313	60
Fluorine as F	165 - 692	305
Aluminum as Al	9,310 - 45,200	30,743
Phosphorus as P	238 - 1,560	956
Chlorine as Cl	<10 - 190	low 14 high 140
Potassium as K	3,800 - 55,100	low 6,888 high 40,875
Calcium as Ca	99 - 4,890	3,245
Titanium as Ti	30 - 805	318
Vanadium as V	114 - 315	194
Chromium as Cr	59 - 566	140
Manganese as Mn	<10 - 1,370	671
Iron as Fe	31,300 - 370,000	45,236
Cobalt as Co	11 - 463	27
Nickel as Ni	<10 - 399	low 35 high 304
Copper as Cu	29 - 1,820	98
Zinc as Zn	68.3 - 846	94
Arsenic as As	39 - 6,920	low 249 high 6,225
Selenium as Se	<1 - 12	low 2.1 high 11
Strontium as Sr	34 - 439	221
Molybdenum as Mo	<0.6 - 3,416	4
Cadmium as Cd	.3 - 51	.8
Tin as Sn	52 - 308	103
Antimony as Sb	79 - 290	192
Boron as B	42 - 104	84
Barium as Ba	5 - 25	13
Mercury as Hg	.007 - 9.46	1.03
Lead as Pb	<1 - 646	23
Bismuth as Bi	<10 - 14	<11
Sulphate as SO_4	14,000 - 318,000	45,845
Carbonate as CO_3	<1,000 - 73,800	8,200

PART C

RED LAKE AREA, ONTARIO

The analytical results that follow are based on representative tailings samples taken at 10 Red Lake area mining properties. These properties contain an aggregate total of over 28,000,000 tons of mineral tailings. Some properties in the camp were not sampled.

Sample Code	H8	MM	NN	KK
Production Commenced	1930	1935	1939	1940
Sodium as Na	21,800	19,700	16,600	886
Magnesium as Mg	4,880	6,400	12,200	22,800
Nitrogen as N	30.6	19.5	36.3	36.4
Fluorine as F	512	227	176	207
Aluminum as Al	50,000	35,700	26,900	4,230
Phosphorus as P	394	808	552	238
Chlorine as Cl	17	17	83	17
Potassium as K	26,800	15,600	12,800	2,560
Calcium as Ca	1,240	3,150	6,270	3,250
Titanium as Ti	394	42	374	119
Vanadium as V	54	56	114	112
Chromium as Cr	38	69	179	39
Manganese as Mn	430	404	667	1,220
Iron as Fe	19,800	37,100	51,400	31,300
Cobalt as Co	3	14	42	6
Nickel as Ni	<10	51	608	38
Copper as Cu	10	59	30	29
Zinc as Zn	191	98.4	99.6	157
Arsenic as As	57	720	1,340	767
Selenium as Se	1	<1	1	<1
Strontium as Sr	71	181	137	51
Molybdenum as Mo	1.6	<0.6	<2.2	<0.6
Cadmium as Cd	4.0	0.9	0.9	0.6
Tin as Sn	64	55	89	26
Antimony as Sb	79	208	187	586
Boron as B	92	104	87	87
Barium as Ba	29	15	45	10
Mercury as Hg	<.005	.596	.173	.248
Lead as Pb	26	8	23	8
Bismuth as Bi	<10	<10	47	<10
Sulphate as SO_4	34,700	32,600	66,100	18,500
Carbonate as CO_3	5,400	1,000	5,400	311,000

Sample Code	3B13	3B14	3B15	TT
Production Commenced	1938	1936	1948	1949
Sodium as Na	2,680	26,800	693	780
Magnesium as Mg	13,800	3,020	8,610	23,000
Nitrogen as N	8.3	27.8	11.2	33.5
Fluorine as F	432	392	352	173
Aluminum as Al	17,400	50,200	24,500	14,000
Phosphorus as P	720	220	104	785
Chlorine as Cl	130	10	50	58
Potassium as K	15,900	25,100	7,020	3,900
Calcium as Ca	3,270	779	3,460	5,560
Titanium as Ti	2,300	350	1,050	512
Vanadium as V	198	78	198	139
Chromium as Cr	446	19	19	585
Manganese as Mn	1,300	1,250	1,480	1,360
Iron as Fe	83,900	14,700	87,900	71,400
Cobalt as Co	48	3	28	41
Nickel as Ni	309	25	129	215
Copper as Cu	129	49	79	78
Zinc as Zn	149	156	1,360	331
Arsenic as As	5,780	58	6,920	6,990
Selenium as Se	5	4	6	<1
Strontium as Sr	20	61	30	25
Molybdenum as Mo	1.7	1.7	1.1	<0.6
Cadmium as Cd	1.3	2.7	1.3	3.8
Tin as Sn	103	92	105	91
Antimony as Sb	348	<10	280	556
Boron as B	103	109	85	116
Barium as Ba	16	16	8	<10
Mercury as Hg	.149	.115	1.36	.153
Lead as Pb	22	17	51	45
Bismuth as Bi	20	<10	<10	<10
Sulphate as SO_4	20,000	16,300	39,000	48,600
Carbonate as CO_3	<1,000	1,800	<1,000	5,400

Sample Code			Data Range	Typical Composition
Production Commenced	WW 1948	UU 1937		
Sodium as Na	3,270	18,900	693 - 26,800	Low 1,662 High 20,760
Magnesium as Mg	10,900	6,680	3,020-23,000	11,229
Nitrogen as N	89.2	19.5	8.3 - 89.2	31
Fluorine as F	390	412	173 - 512	327
Aluminum as Al	30,000	41,800	4,230-50,200	32,278
Phosphorus as P	1,190	407	104 - 1,190	542
Chlorine as Cl	17	<10	<10 - 130	41
Potassium as K	17,100	15,800	2,560-26,800	14,258
Calcium as Ca	4,910	3,890	779-6,270	3,889
Titanium as Ti	1,050	388	42-2,300	726
Vanadium as V	165	57	54 - 198	117
Chromium as Cr	115	89	19 - 585	71
Manganese as Mn	972	319	319 - 1,480	940
Iron as Fe	59,300	20,800	14,700-87,900	47,760
Cobalt as Co	33	3	3 - 48	22
Nickel as Ni	50	<10	<10 - 603	93
Copper as Cu	106	20	10 - 129	59
Zinc as Zn	115	558	98.4-1,360	162
Arsenic as As	9,620	1,270	57 - 9,620	4,176
Selenium as Se	3	<1	<1 - 6	2.4
Strontium as Sr	65	158	20 - 181	80
Molybdenum as Mo	<0.6	<0.6	<0.6 - <2.2	<1.1
Cadmium as Cd	1.2	0.9	0.6 - 4.0	1.8
Tin as Sn	75	67	26 - 105	67
Antimony as Sb	225	<10	<10 - 586	309
Boron as B	96	107	85 - 116	99
Barium as Ba	14	10	8 - 45	17
Mercury as Hg	.062	<.005	<.005-1.36	.287
Lead as Pb	29	125	8 - 125	25
Bismuth as Bi	<10	<10	<10 - 47	<10
Sulphate as SO_4	39,000	30,500	16,300-66,100	34,530
Carbonate as CO_3	5,400	3,600	<1,000-311,000	3,333

PART D

WAWA - MISSANABIE AREA, ONTARIO

The analytical results quoted here are based on representative tailings samples taken at 4 Wawa-Missanabie area mining properties. These specific properties contain an aggregate total of over 3,000,000 tons of mineral tailings. Many small properties in the area were not sampled.

Sample Code	3B19	3B20	3B3	3B5
Production Commenced	1968	1929	1947	1904
Sodium as Na	16,700	9,990	13,800	12,000
Magnesium as Mg	4,640	4,550	5,270	2,950
Nitrogen as N	120	61.4	19.5	151
Fluorine as F	232	272	326	156
Aluminum as Al	25,900	27,000	28,600	24,000
Phosphorus as P	1,200	890	157	1,350
Chlorine as Cl	45	25	10	20
Potassium as K	25,200	29,700	10,600	8,250
Calcium as Ca	2,560	2,370	2,440	3,630
Titanium as Ti	320	270	370	1,300
Vanadium as V	118	119	78	79
Chromium as Cr	108	129	68	226
Manganese as Mn	621	940	107	314
Iron as Fe	49,600	66,800	15,500	92,900
Cobalt as Co	25	61	20	16
Nickel as Ni	51	64	<10	<10
Copper as Cu	59	168	39	98
Zinc as Zn	138	109	48.8	58.9
Arsenic as As	592	752	59	5,780
Selenium as Se	<1	6	<1	2
Strontium as Sr	104	104	164	122
Molybdenum as Mo	1.1	1.1	2.1	2.2
Cadmium as Cd	0.8	1.0	0.3	1.2
Tin as Sn	105	117	52	116
Antimony as Sb	70	520	130	208
Boron as B	58	72	100	93
Barium as Ba	12	12	10	16
Mercury as Hg	.121	1.11	.020	2350
Lead as Pb	9	64	17	38
Bismuth as Bi	<10	70	<10	<10
Sulphate as SO_4	20,700	46,200	13,500	29,900
Carbonate as CO_3	12,600	66,600	<1,000	<1,000

Sample Code	Data Range	Typical Composition
Production Commenced	-	-
Sodium as Na	9,990 - 16,700	13,123
Magnesium as Mg	2,950 - 4,640	4,353
Nitrogen as N	19.5 - 151	88
Fluorine as F	156 - 326	247
Aluminum as Al	24,000 - 28,600	26,375
Phosphorus as P	157 - 1,350	899
Chlorine as Cl	10 - 45	25
Potassium as K	8,250 - 29,700	18,438
Calcium as Ca	2,370 - 3,630	2,750
Titanium as Ti	270 - 1,300	320
Vanadium as V	78 - 119	99
Chromium as Cr	68 - 226	133
Manganese as Mn	107 - 940	496
Iron as Fe	15,500 - 92,900	56,200
Cobalt as Co	16 - 61	31
Nickel as Ni	<10 - 64	<34
Copper as Cu	39 - 168	91
Zinc as Zn	48.8 - 138	89
Arsenic as As	59 - 5,780	672
Selenium as Se	<1 - 6	<3
Strontium as Sr	104 - 164	124
Molybdenum as Mo	1.1 - 2.2	1.6
Cadmium as Cd	0.3 - 1.2	.8
Tin as Sn	52 - 117	98
Antimony as Sb	70 - 520	232
Boron as B	58 - 100	81
Barium as Ba	10 - 16	13
Mercury as Hg	.020 - 2,350	.417
Lead as Pb	9 - 64	32
Bismuth as Bi	<10 - 70	<10
Sulphate as SO_4	13,500 - 46,200	27,575
Carbonate as CO_3	<1,000 - 66,600	<4,867

PART E

PICKLE LAKE - CENTRAL PATRICIA AREA

The analytical results that follow are based on representative mineral tailings samples taken from 9 tailings areas located on 2 mining properties in the Pickle Lake - Central Patricia gold area. The specific properties sampled contain an aggregate total of over 4,900,000 tons of tailings. Other small properties in the area were not sampled.

Sample Code	3B24	3B25	3B26	3B27
Production Commenced	1935	1935	1935	1935
Sodium as Na	8,230	3,710	11,600	6,410
Magnesium as Mg	36,600	11,900	7,740	12,000
Nitrogen as N	13.9	50.1	25.1	13.9
Fluorine as F	156	188	156	172
Aluminum as Al	21,700	11,900	23,700	19,800
Phosphorus as P	330	349	140	269
Chlorine as Cl	25	30	30	35
Potassium as K	10,700	5,570	8,990	7,840
Calcium as Ca	4,760	5,380	4,640	6,120
Titanium as Ti	330	270	280	740
Vanadium as V	198	117	77	153
Chromium as Cr	60	77	77	105
Manganese as Mn	764	1,281	677	1,120
Iron as Fe	51,100	61,300	33,500	69,600
Cobalt as Co	34	20	3	2
Nickel as Ni	361	76	<10	37
Copper as Cu	109	108	68	153
Zinc as Zn	109	147	116	191
Arsenic as As	327	1,090	338	335
Selenium as Se	5	<1	<1	<1
Strontium as Sr	73	39	102	50
Molybdenum as Mo	<0.6	<0.6	<0.6	<0.6
Cadmium as Cd	0.8	1.0	0.8	4.1
Tin as Sn	117	98	91	153
Antimony as Sb	200	120	160	569
Boron as B	100	95	104	104
Barium as Ba	40	20	54	23
Mercury as Hg	.247	.165	.683	.450
Lead as Pb	26	13	9	21
Bismuth as Bi	<10	<10	<10	<10
Sulphate as SO_4	27,300	13,900	11,700	30,500
Carbonate as CO_3	27,000	<1,000	5,400	30,600

Sample Code	3B28	3B29	3B30	3B31
Production Commenced	1934	1934	1934	1934
Sodium as Na	988	2,480	1,090	890
Magnesium as Mg	16,800	11,000	8,160	15,400
Nitrogen as N	33.4	75.5	115	22.4
Fluorine as F	248	144	188	268
Aluminum as Al	10,900	16,100	10,900	15,800
Phosphorus as P	2,610	2,220	1,970	1,920
Chlorine as Cl	300	10	20	20
Potassium as K	791	1,990	896	1,480
Calcium as Ca	3,360	3,570	6,070	4,650
Titanium as Ti	80	240	100	<10
Vanadium as V	79	80	80	79
Chromium as Cr	59	79	129	89
Manganese as Mn	1,240	377	403	396
Iron as Fe	259,000	194,000	206,000	227,000
Cobalt as Co	14	3	8	14
Nickel as Ni	<10	<10	<10	10
Copper as Cu	158	149	100	148
Zinc as Zn	198	139	259	247
Arsenic as As	7,750	5,840	9,750	346
Selenium as Se	<1	8	3	2
Strontium as Sr	21	31	20	75
Molybdenum as Mo	<0.6	<0.6	<0.6	<0.6
Cadmium as Cd	2.0	2.6	2.5	2.8
Tin as Sn	186	193	240	203
Antimony as Sb	460	769	370	340
Boron as B	90	103	104	100
Barium as Ba	20	12	8	16
Mercury as Hg	.039	.046	.235	.069
Lead as Pb	90	96	30	60
Bismuth as Bi	<10	<10	<10	<10
Sulphate as SO_4	93,100	90,300	69,700	58,800
Carbonate as CO_3	<1,000	<1,000	<1,000	<1,000

Sample Code	3B32	Data Range	Typical Composition
Production Commenced	1934	-	-
Sodium as Na	793	793 - 11,600	4,021
Magnesium as Mg	14,800	7,740 - 36,600	14,933
Nitrogen as N	36.4	13.9 - 115	34
Fluorine as F	204	144 - 268	192
Aluminum as Al	12,600	10,900 - 23,700	15,933
Phosphorus as P	1,040	140 - 2,220	low 272 high 1,952
Chlorine as Cl	35	10 - 300	26
Potassium as K	893	791 - 10,700	4,350
Calcium as Ca	6,650	3,360 - 6,120	5,022
Titanium as Ti	200	<10 - 740	214
Vanadium as V	<40	<40 - 198	108
Chromium as Cr	188	59 - 188	96
Manganese as Mn	1,150	377 - 1,281	824
Iron as Fe	233,000	33,500 - 259,000	low 53,875 high 223,800
Cobalt as Co	6	2 - 34	12
Nickel as Ni	<10	<10 - 361	<22
Copper as Cu	109	68 - 158	122
Zinc as Zn	228	109 - 259	182
Arsenic as As	3,890	327 - 9,750	low 337 high 5,664
Selenium as Se	10	<1 - 10	<4
Strontium as Sr	30	20 - 102	49
Molybdenum as Mo	<0.6	-	<0.6
Cadmium as Cd	2.5	0.8 - 4.1	2
Tin as Sn	245	91 - 245	170
Antimony as Sb	280	120 - 769	363
Boron as B	106	90 - 106	101
Barium as Ba	20	8 - 54	24
Mercury as Hg	.061	.039 - .683	.222
Lead as Pb	140	9 - 140	43
Bismuth as Bi	<10	-	<10
Sulphate as SO_4	15,600	11,700 - 93,100	45,655
Carbonate as CO_3	<1,000	<1,000 - 30,600	<1,629

PART F

GERALDTON - BEARDMORE AREA

The following analytical results are based on representative tailings samples taken from 8 tailings areas in the Geraldton - Beardmore gold area. These specific areas contain an aggregate total of over 14,700,000 tons of mineral tailings. Several properties in the area were not sampled.

Sample Code	3B35	3B36	3B38	3B39
Production Commenced	1937	1934	1938	1934
Sodium as Na	28,500	12,500	6,320	8,560
Magnesium as Mg	4,910	2,630	14,800	8,460
Nitrogen as N	55.9	92.2	101	101
Fluorine as F	164	212	156	144
Aluminum as Al	37,200	33,700	22,800	19,400
Phosphorus as P	1,700	720	1,040	200
Chlorine as Cl	10	10	70	10
Potassium as K	5,890	20,100	8,300	4,770
Calcium as Ca	3,240	1,750	6,720	5,840
Titanium as Ti	90	40	240	260
Vanadium as V	118	156	79	195
Chromium as Cr	128	88	99	107
Manganese as Mn	383	506	544	1,240
Iron as Fe	58,400	47,500	131,000	52,100
Cobalt as Co	87	19	<1	8
Nickel as Ni	25	<10	<10	5,480
Copper as Cu	128	107	40	29
Zinc as Zn	78.5	126	98.8	156
Arsenic as As	11,600	1,590	15,500	973
Selenium as Se	<1	<1	<1	<1
Strontium as Sr	155	118	93	46
Molybdenum as Mo	<0.6	<0.6	<0.6	<0.6
Cadmium as Cd	1.3	0.8	1.8	1.3
Tin as Sn	138	74	174	103
Antimony as Sb	220	50	370	<10
Boron as B	100	58	100	106
Barium as Ba	27	19	20	27
Mercury as Hg	1.56	2.59	.034	.039
Lead as Pb	4	47	9	<1
Bismuth as Bi	<10	<10	<10	<10
Sulphate as SO_4	48,200	17,400	5,910	6,250
Carbonate as CO_3	23,400	30,600	5,400	16,200

Sample Code	3B40	3B41	3B42	3B43
Production Commenced	1938	1938	1937	1936
Sodium as Na	11,500	9,690	28,100	7,550
Magnesium as Mg	6,420	7,360	5,140	5,910
Nitrogen as N	47.6	36.4	213	322
Fluorine as F	248	216	312	1,720
Aluminum as Al	38,100	25,200	38,600	28,600
Phosphorus as P	399	2,920	2,520	1,320
Chlorine as Cl	<10	30	15	60
Potassium as K	22,700	8,720	7,180	10,600
Calcium as Ca	4,050	4,560	3,200	2,520
Titanium as Ti	698	110	200	320
Vanadium as V	158	116	194	77
Chromium as Cr	128	194	184	87
Manganese as Mn	691	368	485	261
Iron as Fe	67,900	37,000	67,900	39,300
Cobalt as Co	6	19	25	16
Nickel as Ni	436	164	50	38
Copper as Cu	30	107	87	106
Zinc as Zn	109	126	107	155
Arsenic as As	197	3,800	15,200	13,300
Selenium as Se	<1	<1	<1	2
Strontium as Sr	83	122	254	153
Molybdenum as Mo	<0.6	<0.6	<0.6	<0.6
Cadmium as Cd	3.5	0.8	4.7	0.8
Tin as Sn	122	91	114	74
Antimony as Sb	240	120	50	260
Boron as B	102	95	82	102
Barium as Ba	24	27	23	27
Mercury as Hg	.033	.030	.379	.714
Lead as Pb	<1	4	34	25
Bismuth as Bi	<10	<10	<10	>10
Sulphate as SO_4	7,370	13,400	25,100	13,800
Carbonate as CO_3	41,400	5,400	12,600	<1,000

Sample Code	Data Range	Typical Composition
Production Commenced	-	-
Sodium as Na	6,320 - 28,500	14,090
Magnesium as Mg	2,630 - 14,800	6,954
Nitrogen as N	36.4 - 322	72
Fluorine as F	144 - 1,720	207
Aluminum as Al	19,400 - 38,600	30,450
Phosphorus as P	200 - 2,920	1,352
Chlorine as Cl	<10 - 70	27
Potassium as K	4,770 - 22,700	11,033
Calcium as Ca	1,750 - 6,720	3,985
Titanium as Ti	40 - 698	180
Vanadium as V	77 - 195	137
Chromium as Cr	87 - 194	127
Manganese as Mn	261 - 1,240	463
Iron as Fe	37,000 - 131,000	52,871
Cobalt as Co	<1 - 87	16
Nickel as Ni	<10 - 5,480	105
Copper as Cu	29 - 128	79
Zinc as Zn	78.5 - 156	120
Arsenic as As	197 - 15,500	8,852
Selenium as Se	<1 - 2	<1
Strontium as Sr	46 - 254	128
Molybdenum as Mo	-	<0.6
Cadmium as Cd	0.8 - 4.7	1.9
Tin as Sn	74 - 174	111
Antimony as Sb	<10 - 370	187
Boron as B	58 - 106	93
Barium as Ba	19 - 27	24
Mercury as Hg	.030 - 2.59	.672
Lead as Pb	<1 - 47	low 3.8 high 35
Bismuth as Bi	-	<10
Sulphate as SO_4	5,910 - 48,200	12,747
Carbonate as CO_3	<1,000 - 41,400	17,000

PART G

UCHI LAKE - CONFEDERATION LAKE AREA

The analytical results that follow are based on representative mineral tailings samples taken from 2 tailings areas in the Uchi Lake - Confederation Lake area of Ontario. The specific properties sampled contain an aggregate total of less than 900,000 tons of tailings.

Sample Code	3B17	OO	Typical Composition
Production Commenced	1934	1939	-
Sodium as Na	5,520	14,400	9,960
Magnesium as Mg	9,390	9,800	9,595
Nitrogen as N	5.8	373	low 5.8 high 373
Fluorine as F	328	175	252
Aluminum as Al	23,600	24,500	24,050
Phosphorus as P	299	664	482
Chlorine as Cl	20	17	19
Potassium as K	16,900	10,700	13,800
Calcium as Ca	5,220	4,690	4,955
Titanium as Ti	220	1,580	low 220 high 1,580
Vanadium as V	77	169	123
Chromium as Cr	145	69	107
Manganese as Mn	600	802	701
Iron as Fe	50,300	72,500	61,400
Cobalt as Co.	24	22	23
Nickel as Ni	365	<10	low <10 high 365
Copper as Cu	97	50	74
Zinc as Zn	242	119	181
Arsenic as As	58	525	low 58 high 525
Selenium as Se	<1	1	<1
Strontium as Sr	41	125	83
Molybdenum as Mo	1.1	<0.6	.9
Cadmium as Cd	1.5	1.2	1.4
Tin as Sn	103	77	90
Antimony as Sb	130	297	214
Boron as B	108	96	102
Barium as Ba	19	30	25
Mercury as Hg	.065	.472	.269
Lead as Pb	13	9	11
Bismuth as Bi	<10	<10	<10
Sulphate as SO_4	13,600	13,600	13,600
Carbonate as CO_3	16,200	12,600	14,400

PART H

MATACHEWAN AREA

The analytical results that follow are based on 4 representative mineral tailings samples taken from two tailings areas located near Matachewan, Ontario. The specific tailings masses sampled are reported to contain an aggregate total of more than 6,000,000 tons of tailings.

Sample Code	AA	DD	BB	CC
Production Commenced			1934	1934
Sodium as Na	23,300	17,600	29,900	23,400
Magnesium as Mg	4,750	5,020	3,100	3,840
Nitrogen as N	25.0	52.8	33.5	55.6
Fluorine as F	347	308	207	301
Aluminum as Al	49,800	35,600	70,700	60,000
Phosphorus as P	960	910	510	890
Chlorine as Cl	17	33	17	25
Potassium as K	45,600	43,300	68,500	72,000
Calcium as Ca	2,040	3,340	3,270	2,880
Titanium as Ti	185	350	112	86
Vanadium as V	155	151	80	115
Chromium as Cr	145	118	79	58
Manganese as Mn	436	865	203	413
Iron as Fe	34,900	46,200	20,700	28,600
Cobalt as Co	6	14	3	6
Nickel as Ni	303	64	77	<10
Copper as Cu	126	206	29	19
Zinc as Zn	155	1,000	19.8	76.8
Arsenic as As	300	285	248	336
Selenium as Se	2	3	<1	<1
Strontium as Sr	51	46	81	60
Molybdenum as Mo	1.1	<0.6	<0.6	<0.6
Cadmium as Cd	1.5	3.8	0.9	0.6
Tin as Sn	40	62	77	46
Antimony as Sb	92	268	138	334
Boron as B	74	82	98	95
Barium as Ba	24	15	60	19
Mercury as Hg	.182	.033	.073	.054
Lead as Pb	740	1,280	22	11
Bismuth as Bi	<10	18	<10	<10
Sulphate as SO_4	28,700	38,400	38,900	45,400
Carbonate as CO_3	9,000	48,600	9,000	41,400

Sample Code	Data Range	Typical Composition
Production Commenced	-	-
Sodium as Na	17,600 - 29,900	23,550
Magnesium as Mg	3,100 - 5,020	4,178
Nitrogen as N	25.0 - 55.6	42
Fluorine as F	207 - 347	291
Aluminum as Al	35,600 - 70,700	54,025
Phosphorus as P	510 - 960	818
Chlorine as Cl	17 - 33	23
Potassium as K	43,300 - 72,000	57,350
Calcium as Ca	2,040 - 3,340	2,883
Titanium as Ti	86 - 350	183
Vanadium as V	80 - 155	125
Chromium as Cr	58 - 145	100
Manganese as Mn	203 - 865	481
Iron as Fe	20,700 - 46,200	32,600
Cobalt as Co	3 - 14	7
Nickel as Ni	<10 - 303	low 71 high 303
Copper as Cu	19 - 206	low 24 high 166
Zinc as Zn	19.8 - 1,000	low 84 high 1,000
Arsenic as As	248 - 336	292
Selenium as Se	<1 - 3	<2
Strontium as Sr	46 - 81	60
Molybdenum as Mo	<0.6 - 1.1	<.7
Cadmium as Cd	0.6 - 3.8	1.7
Tin as Sn	46 - 77	56
Antimony as Sb	92 - 334	208
Boron as B	74 - 98	87
Barium as Ba	15 - 60	30
Mercury as Hg	.033 - .182	.086
Lead as Pb	11 - 1,280	low 17 high 1,010
Bismuth as Bi	<10 - 18	<12
Sulphate as SO_4	28,700 - 45,400	37,850
Carbonate as CO_3	9,000 - 48,600	low 9,000 high 45,000

PART I

BANCROFT AREA

Only one representative mineral tailings sample was obtained from a small abandoned gold property in the Bancroft area. The tailings area contains less than 130,000 tons of tailings.

Sample Code	S
Production Commenced	1902
Sodium as Na	10,800
Magnesium as Mg	1,290
Nitrogen as N	189
Fluorine as F	239
Aluminum as Al	11,700
Phosphorus as P	1,550
Chlorine as Cl	42
Potassium as K	1,290
Calcium as Ca	4,460
Titanium as Ti	1,850
Vanadium as V	1,030
Chromium as Cr	129
Manganese as Mn	2,870
Iron as Fe	374,000
Cobalt as Co	20
Nickel as Ni	<10
Copper as Cu	99
Zinc as Zn	99.1
Arsenic as As	149
Selenium as Se	11
Strontium as Sr	120
Molybdenum as Mo	<0.6
Cadmium as Cd	3.0
Tin as Sn	147
Antimony as Sb	264
Boron as B	88
Barium as Ba	14
Mercury as Hg	1.13
Lead as Pb	42
Bismuth as Bi	<10
Sulphate as SO_4	134,000
Carbonate as CO_3	<1,000

APPENDIX B

ANALYTICAL RESULTS

MINERAL TAILINGS

SILVER OPERATIONS

Analytical Results
Mineral Tailings
Silver Operations

PART A

COBALT AREA, ONTARIO

The analytical results that follow are based on representative mineral tailings samples taken from 16 tailings areas located on more than 12 mining properties in the Cobalt silver area. The specific areas sampled contain an aggregate of at least 4,000,000 tons of tailings. Several properties in the area were not sampled.

Sample Code	F	I	Q	V
Production Commenced	1905	1904	1904	1904
Sodium as Na	38,900	31,200	23,700	25,400
Magnesium as Mg	8,670	14,400	10,600	7,730
Nitrogen as N	<2.8	14.0	14.0	38.9
Fluorine as F	78	113	315	236
Aluminum as Al	47,200	50,000	50,400	40,400
Phosphorus as P	465	475	691	2,800
Chlorine as Cl	<10	<10	<10	<10
Potassium as K	6,520	6,720	10,800	4,060
Calcium as Ca	4,670	4,190	3,260	4,260
Titanium as Ti	190	267	1,200	681
Vanadium as V	195	156	198	159
Chromium as Cr	263	369	99	89
Manganese as Mn	400	360	455	624
Iron as Fe	43,500	40,900	49,100	51,200
Cobalt as Co	95	142	173	2,100
Nickel as Ni	76	63	103	10,000
Copper as Cu	419	175	159	813
Zinc as Zn	107	282	801	545
Arsenic as As	594	652	1,040	11,700
Selenium as Se	<1	<1	1	4
Strontium as Sr	77	93	46	67
Molybdenum as Mo	<0.6	<0.6	<0.6	<0.6
Cadmium as Cd	1.1	1.9	3.2	2.4
Tin as Sn	76	87	55	81
Antimony as Sb	99	93	19	445
Boron as B	85	145	88	88
Barium as Ba	27	42	63	14
Mercury as Hg	.723	.288	.608	16.6
Lead as Pb	19	33	1,130	91
Bismuth as Bi	12	15	<10	90
Sulphate as SO_4	40,300	6,010	13,600	9,700
Carbonate as CO_3	<1,000	<1,000	3,600	7,200

Sample Code	B2	C3	G7	J10
Production Commenced			1908	1906
Sodium as Na	24,400	21,000	25,800	15,700
Magnesium as Mg	7,680	7,370	6,170	8,560
Nitrogen as N	61.5	143	53.0	36.1
Fluorine as F	834	352	276	148
Aluminum as Al	42,700	30,900	51,900	29,400
Phosphorus as P	933	985	451	519
Chlorine as Cl	17	17	17	10
Potassium as K	12,800	9,020	13,600	8,370
Calcium as Ca	4,030	3,200	1,540	5,080
Titanium as Ti	943	1,580	354	2,470
Vanadium as V	192	222	138	256
Chromium as Cr	106	38	106	239
Manganese as Mn	490	592	251	1,170
Iron as Fe	42,700	56,500	30,400	60,700
Cobalt as Co	286	566	24	189
Nickel as Ni	100	88	<10	103
Copper as Cu	192	281	68	159
Zinc as Zn	346	233	86.8	229
Arsenic as As	5,120	7,110	174	876
Selenium as Se	1	<1	<1	<1
Strontium as Sr	49	55	58	63
Molybdenum as Mo	<0.6	<0.6	3.8	1.1
Cadmium as Cd	1.2	1.2	0.6	0.9
Tin as Sn	64	80	71	67
Antimony as Sb	10	176	141	239
Boron as B	103	100	88	93
Barium as Ba	38	29	19	40
Mercury as Hg	2.54	2.37	.052	.154
Lead as Pb	69	314	8	46
Bismuth as Bi	<10	53	<10	<10
Sulphate as SO_4	12,600	20,100	2,760	11,900
Carbonate as CO_3	9,000	9,000	<1,000	5,400

Sample Code	K11	U	3B12	N14
Production Commenced	-	1905	-	1908
Sodium as Na	63,400	23,600	24,100	17,500
Magnesium as Mg	6,340	13,200	4,940	6,350
Nitrogen as N	33.4	36.2	106	86.5
Fluorine as F	212	226	297	263
Aluminum as Al	47,400	60,400	37,400	39,300
Phosphorus as P	564	868	976	4,460
Chlorine as Cl	10	<10	35	10
Potassium as K	5,940	9,900	7,910	6,450
Calcium as Ca	3,070	7,180	2,270	2,880
Titanium as Ti	1,650	1,270	1,990	1,200
Vanadium as V	142	971	158	142
Chromium as Cr	119	155	79	119
Manganese as Mn	455	680	524	516
Iron as Fe	47,700	56,700	53,300	60,400
Cobalt as Co	80	490	491	4,060
Nickel as Ni	64	278	334	2,070
Copper as Cu	40	699	375	1,390
Zinc as Zn	99.0	913	316	347
Arsenic as As	41	6,800	5,600	11,700
Selenium as Se	<1	<1	2	10
Strontium as Sr	61	82	50	27
Molybdenum as Mo	<0.6	<0.6	2.2	2.2
Cadmium as Cd	0.6	2.9	2.4	0.9
Tin as Sn	84	72	99	69
Antimony as Sb	229	468	244	531
Boron as B	95	84	100	115
Barium as Ba	35	42	24	30
Mercury as Hg	.581	3.31	5.41	2.54
Lead as Pb	11	961	128	75
Bismuth as Bi	<10	<10	27	106
Sulphate as SO_4	7,790	11,100	11,300	6,170
Carbonate as CO_3	2,000	9,000	9,000	5,400

Sample Code	I9	O	J	II
Production Commenced	1917	1905	1905	1907
Sodium as Na	10,300	25,000	33,100	8,650
Magnesium as Mg	9,960	9,700	15,000	12,300
Nitrogen as N	47.3	25.1	16.7	19.6
Fluorine as F	134	258	161	178
Aluminum as Al	26,600	46,000	46,600	18,100
Phosphorus as P	386	1,440	511	1,410
Chlorine as Cl	<10	<10	<10	17
Potassium as K	9,660	14,000	8,016	9,130
Calcium as Ca	6,180	10,400	3,310	6,150
Titanium as Ti	1,500	307	244	190
Vanadium as V	199	120	160	246
Chromium as Cr	129	130	110	143
Manganese as Mn	1,150	509	401	1,330
Iron as Fe	49,300	46,400	41,100	68,000
Cobalt as Co	189	8	264	559
Nickel as Ni	39	182	52	174
Copper as Cu	139	210	650	134
Zinc as Zn	159	200	361	298
Arsenic as As	1,180	8,330	952	8,600
Selenium as Se	<1	<1	1	<1
Strontium as Sr	52	58	74	36
Molybdenum as Mo	1.1	<0.6	<0.6	2.1
Cadmium as Cd	0.6	1.6	1.9	1.1
Tin as Sn	82	233	78	3
Antimony as Sb	222	1,590	148	10
Boron as B	90	115	2	98
Barium as Ba	5	57	50	<10
Mercury as Hg	.276	.769	.340	.485
Lead as Pb	27	267	107	22
Bismuth as Bi	14	<10	20	19
Sulphate as SO_4	10,300	2,980	11,500	28,900
Carbonate as CO_3	9,000	9,150	<1,000	5,400

Sample Code	VV	015	R
Production Commenced	1908	1906	-
Sodium as Na	10,600	23,900	68,900
Magnesium as Mg	12,100	6,740	5,720
Nitrogen as N	25.0	100	55.5
Fluorine as F	321	243	243
Aluminum as Al	24,200	36,200	53,800
Phosphorus as P	1,370	2,020	617
Chlorine as Cl	17	10	<10
Potassium as K	8,830	6,840	8,240
Calcium as Ca	6,790	2,832	2,420
Titanium as Ti	2,060	1,040	582
Vanadium as V	166	167	116
Chromium as Cr	349	107	116
Manganese as Mn	1,400	566	369
Iron as Fe	65,600	46,900	41,900
Cobalt as Co	440	1,490	84
Nickel as Ni	202	862	88
Copper as Cu	97	693	262
Zinc as Zn	107	342	194
Arsenic as As	5,330	4,700	718
Selenium as Se	2	1	<1
Strontium as Sr	56	57	61
Molybdenum as Mo	<0.6	<0.6	<0.6
Cadmium as Cd	1.2	1.2	1.4
Tin as Sn	76	65	47
Antimony as Sb	29	234	143
Boron as B	91	73	57
Barium as Ba	24	25	20
Mercury as Hg	1.82	8.36	.421
Lead as Pb	66	66	370
Bismuth as Bi	49	<10	<10
Sulphate as SO_4	8,850	15,700	10,000
Carbonate as CO_3	7,200	2,000	2,500

Sample Code	Data Range	Typical Composition
Production Commenced	-	--
Sodium as Na	8,650 - 68,900	27,113
Magnesium as Mg	4,940 - 15,000	9,133
Nitrogen as N	<2.8 - 143	48
Fluorine as F	78 - 834	257
Aluminum as Al	18,100 - 60,400	40,995
Phosphorus as P	386 - 4,460	1,155
Chlorine as Cl	<10 - 35	<13
Potassium as K	4,060 - 14,000	3,779
Calcium as Ca	1,540 - 10,400	4,406
Titanium as Ti	190 - 2,470	1,038
Vanadium as V	116 - 971	216
Chromium as Cr	38 - 369	151
Manganese as Mn	251 - 1,400	644
Iron as Fe	30,400 - 68,000	50,121
Cobalt as Co	8 - 4,060	426
Nickel as Ni	<10 - 10,000	166
Copper as Cu	40 - 1,390	309
Zinc as Zn	86.8 - 913	314
Arsenic as As	41 - 11,700	4,275
Selenium as Se	<1 - 10	<1.3
Strontium as Sr	27 - 93	59
Molybdenum as Mo	<0.6 - 3.8	<1.1
Cadmium as Cd	0.6 - 3.2	1.5
Tin as Sn	3 - 233	74
Antimony as Sb	10 - 1,590	267
Boron as B	2 - 145	95
Barium as Ba	5 - 63	34
Mercury as Hg	.052 - 16.6	1.335
Lead as Pb	8 - 1,130	101
Bismuth as Bi	<10 - 106	26
Sulphate as SO_4	2,760 - 40,300	12,714
Carbonate as CO_3	1,000 - 9,150	5,203

PART B

GOWGANDA AREA, ONTARIO

The following analytical results are based on 2 representative samples of mineral tailings taken at 1 mining property in the Gowganda silver area. The samples represent at least 1,500,000 tons of mineral tailings.

Sample Code	EE	FF	Typical Composition
Production Commenced	1908	1908	-
Sodium as Na	7,970	8,130	8,050
Magnesium as Mg	8,550	11,900	10,225
Nitrogen as N	39.1	44.6	42
Fluorine as F	432	152	292
Aluminum as Al	16,700	23,100	19,900
Phosphorus as P	603	444	524
Chlorine as Cl	17	17	17
Potassium as K	8,850	12,400	10,625
Calcium as Ca	2,750	7,180	4,955
Titanium as Ti	881	851	866
Vanadium as V	197	164	181
Chromium as Cr	256	220	238
Manganese as Mn	1,141	967	1,054
Iron as Fe	58,900	56,200	57,550
Cobalt as Co	474	252	363
Nickel as Ni	243	137	190
Copper as Cu	138	86	112
Zinc as Zn	118	95.7	107
Arsenic as As	7,870	7,460	7,665
Selenium as Se	3	1	2
Strontium as Sr	21	38	30
Molybdenum as Mo	1.7	1.1	1.4
Cadmium as Cd	0.9	1.4	1.2
Tin as Sn	51	71	61
Antimony as Sb	139	231	185
Boron as B	77	85	81
Barium as Ba	5	24	15
Mercury as Hg	1.42	.524	.972
Lead as Pb	29	24	27
Bismuth as Bi	26	<10	18
Sulphate as SO_4	20,400	11,700	16,050
Carbonate as CO_3	5,400	12,600	9,000

APPENDIX C

ANALYTICAL RESULTS

MINERAL TAILINGS

BASE METAL SULPHIDE OPERATIONS

(Cu, Ni, Pb, Zn)

Analytical Results

Mineral Tailings

Base Metal Sulphide Operations

(Cu, Ni, Pb, Zn)

PART A

TIMMINS-KIRKLAND LAKE AREAS

The results quoted here are based on representative tailings samples taken at three Timmins - Kirkland Lake area mining properties. These specific properties contain an aggregate total of over 40,000,000 tons of mineral tailings.

Sample Code	G	E5	3B9	3B10
Production Commenced	1966	1965	1966	1966
Sodium as Na	4,680	1,170	18,700	1,390
Magnesium as Mg	34,500	17,300	5,730	11,900
Nitrogen as N	92.0	55.7	47.4	39.1
Fluorine as F	162	1,137	186	324
Aluminum as Al	8,360	17,800	36,500	34,600
Phosphorus as P	185	632	330	144
Chlorine as Cl	<10	17	30	10
Potassium as K	1,290	3,690	16,700	10,900
Calcium as Ca	8,460	583	2,370	995
Titanium as Ti	1,420	92	472	172
Vanadium as V	119	194	40	<40
Chromium as Cr	756	194	89	60
Manganese as Mn	806	1,180	188	368
Iron as Fe	255,000	171,000	29,500	136,000
Cobalt as Co	70	568	39	160
Nickel as Ni	78	76	90	13
Copper as Cu	677	2,330	296	945
Zinc as Zn	1,274	4,060	1,660	4,160
Arsenic as As	249	632	1,010	776
Selenium as Se	2	85	68	35
Strontium as Sr	42	16	149	298
Molybdenum as Mo	2.2	1.1	2.8	3.9
Cadmium as Cd	3.8	8.0	6.9	14.4
Tin as Sn	169	140	81	158
Antimony as Sb	323	119	226	115
Boron as B	435	87	100	92
Barium as Ba	14	29	51	40
Mercury as Hg	.604	<.005	.283	.157
Lead as Pb	53	29	51	1,293
Bismuth as Bi	24	46	45	57
Sulphate as SO_4	203,400	45,400	40,300	274,000
Carbonate as CO_3	<1,000	<1,000	2,000	<1,000

Sample Code	Data Range	Typical Composition
Production Commenced	-	-
Sodium as Na	1,170 - 18,700	2,413
Magnesium as Mg	5,730 - 34,500	17,358
Nitrogen as N	39.1 - 92.0	47
Fluorine as F	162 - 1,137	224
Aluminum as Al	8,360 - 36,500	24,315
Phosphorus as P	144 - 632	220
Chlorine as Cl	<10 - 30	17
Potassium as K	1,290 - 16,700	8,145
Calcium as Ca	583 - 8,460	3,102
Titanium as Ti	92 - 1,420	539
Vanadium as V	<40 - 194	98
Chromium as Cr	60 - 756	114
Manganese as Mn	188 - 1,180	636
Iron as Fe	29,500 - 255,000	153,500
Cobalt as Co	39 - 568	90
Nickel as Ni	13 - 90	64
Copper as Cu	296 - 2,330	639
Zinc as Zn	1,274 - 4,160	2,789
Arsenic as As	249 - 1,010	667
Selenium as Se	2 - 85	63
Strontium as Sr	16 - 298	126
Molybdenum as Mo	1.1 - 3.9	2.5
Cadmium as Cd	3.8 - 14.4	8
Tin as Sn	81 - 169	137
Antimony as Sb	115 - 323	196
Boron as B	87 - 435	93
Barium as Ba	14 - 51	34
Mercury as Hg	<.005 - .604	.262
Lead as Pb	29 - 1,293	44
Bismuth as Bi	24 - 57	43
Sulphate as SO_4	40,300 - 274,000	140,775
Carbonate as CO_3	<1,000 - 2,000	<1,250

PART B

SAULT STE. MARIE - SUDBURY - TEMAGAMI AREA

The following analytical results are based on representative tailings samples taken from thirteen tailings areas in the Sault Ste. Marie - Sudbury - Temagami area. These specific properties contain an aggregate total of over 390,000,000 tons of mineral tailings. Many properties in the area were not sampled.

Sample Code	B	C	3B11	3B16
Production Commenced	1953	1953	1933	1967
Sodium as Na	7,930	7,570	3,240	10,200
Magnesium as Mg	20,000	14,900	10,400	11,400
Nitrogen as N	5.6	2.8	<2.8	<2.8
Fluorine as F	98	180	151	520
Aluminum as Al	16,600	12,600	34,200	23,000
Phosphorus as P	477	468	240	330
Chlorine as Cl	<10	<10	15	70
Potassium as K	4,660	4,780	8,180	4,690
Calcium as Ca	9,420	6,770	3,810	3,710
Titanium as Ti	1,640	1,490	1,500	1,580
Vanadium as V	1,350	717	266	717
Chromium as Cr	228	239	324	156
Manganese as Mn	962	976	1,030	547
Iron as Fe	115,000	171,000	166,000	375,000
Cobalt as Co	34	64	167	143
Nickel as Ni	527	4,130	4,210	4,570
Copper as Cu	278	707	780	381
Zinc as Zn	139	189	171	146
Arsenic as As	198	229	209	88
Selenium as Se	3	<1	59	10
Strontium as Sr	125	73	50	153
Molybdenum as Mo	0.6	0.6	3.1	1.1
Cadmium as Cd	9.0	4.8	2.6	4.4
Tin as Sn	99	141	196	287
Antimony as Sb	151	217	232	500
Boron as B	265	75	100	96
Barium as Ba	27	21	34	313
Mercury as Hg	.063	.035	.013	.018
Lead as Pb	60	30	12	9
Bismuth as Bi	13	<10	32	<10
Sulphate as SO_4	18,600	66,700	122,000	165,000
Carbonate as CO_3	<1,000	<1,000	5,400	<1,000

Sample Code	3B1	3B2	3B22	L
Production Commenced	1967	1967	1959	1966
Sodium as Na	4,860	17,200	13,700	7,830
Magnesium as Mg	11,200	8,340	6,100	8,130
Nitrogen as N	44.5	2.8	2.8	13.9
Fluorine as F	291	296	260	181
Aluminum as Al	26,000	38,900	22,047	31,200
Phosphorus as P	195	263	380	472
Chlorine as Cl	10	<10	210	<10
Potassium as K	13,600	17,900	5,510	6,940
Calcium as Ca	4,860	3,290	2,070	3,770
Titanium as Ti	399	205	1,450	491
Vanadium as V	78	119	157	40
Chromium as Cr	97	89	98	139
Manganese as Mn	486	357	630	218
Iron as Fe	48,500	39,900	370,000	35,700
Cobalt as Co	87	20	86	28
Nickel as Ni	10	<10	5,240	<10
Copper as Cu	730	367	541	2,030
Zinc as Zn	165	139	207	49.6
Arsenic as As	263	139	157	535
Selenium as Se	4	6	4	<1
Strontium as Sr	42	63	186	67
Molybdenum as Mo	2.1	2.2	<0.6	<0.6
Cadmium as Cd	0.9	0.9	4.2	0.5
Tin as Sn	109	75	336	52
Antimony as Sb	<10	10	480	255
Boron as B	101	103	95	116
Barium as Ba	24	35	31	40
Mercury as Hg	.025	.066	.014	.114
Lead as Pb	17	69	17	15
Bismuth as Bi	<10	<10	<10	<10
Sulphate as SO_4	44,000	40,500	148,000	13,200
Carbonate as CO_3	9,000	9,000	<1,000	<1,000

Sample Code	M	W	X	Y
Production Commenced	1952	1933	1967	1957
Sodium as Na	4,640	7,570	8,950	16,000
Magnesium as Mg	25,100	7,970	15,700	7,610
Nitrogen as N	86.6	55.6	55.9	52.8
Fluorine as F	569	203	264	278
Aluminum as Al	27,900	28,200	36,900	32,700
Phosphorus as P	441	666	825	760
Chlorine as Cl	<10	25	25	12
Potassium as K	3,650	9,560	12,700	8,980
Calcium as Ca	5,330	3,780	7,550	3,800
Titanium as Ti	1,700	1,570	2,380	1,910
Vanadium as V	40	199	239	117
Chromium as Cr	30	269	417	107
Manganese as Mn	247	876	835	761
Iron as Fe	13,700	105,000	96,300	136,000
Cobalt as Co	<1	64	70	52
Nickel as Ni	38	1,680	736	1,900
Copper as Cu	<10	608	229	566
Zinc as Zn	19.7	110	129	244
Arsenic as As	<20	269	258	195
Selenium as Se	<1	15	10	39
Strontium as Sr	88	73	136	174
Molybdenum as Mo	<0.6	<0.6	<0.6	<0.6
Cadmium as Cd	1.1	1.9	1.9	2.6
Tin as Sn	40	74	85	83
Antimony as Sb	386	245	252	197
Boron as B	40	81	91	44
Barium as Ba	56	14	14	<10
Mercury as Hg	.189	.088	.034	<.005
Lead as Pb	376	23	21	15
Bismuth as Bi	37	<10	<10	<10
Sulphate as SO_4	61,300	57,700	18,800	97,000
Carbonate as CO_3	<1,000	<1,000	<1,000	<1,000

Sample Code	Z	Data Range	Typical Composition
Production Commenced	1974		
Sodium as Na	99.6	99.6 - 17,200	9,141
Magnesium as Mg	17,600	6,100 - 25,100	12,650
Nitrogen as N	55.5	<2.8 - 86.6	30
Fluorine as F	284	98 - 569	275
Aluminum as Al	7,270	7,270 - 38,900	27,521
Phosphorus as P	247	195 - 825	443
Chlorine as Cl	25	<10 - 210	<15
Potassium as K	896	896 - 17,900	8,429
Calcium as Ca	1,790	1,790 - 9,420	4,612
Titanium as Ti	887	205 - 2,380	1,323
Vanadium as V	159	40 - 1,350	194
Chromium as Cr	1,040	30 - 1,040	249
Manganese as Mn	867	218 - 1,030	676
Iron as Fe	53,300	13,700 - 375,000	89,127
Cobalt as Co	145	<1 - 167	80
Nickel as Ni	2,720	<10 - 5,240	1,983
Copper as Cu	2,020	<10 - 2,030	519
Zinc as Zn	69.7	19.7 - 244	164
Arsenic as As	239	<20 - 535	232
Selenium as Se	4	<1 - 59	8
Strontium as Sr	5	5 - 186	103
Molybdenum as Mo	<0.6	<0.6 - 3.1	<1
Cadmium as Cd	2.1	0.5 - 9.0	2.3
Tin as Sn	48	40 - 336	125
Antimony as Sb	49	<10 - 500	292
Boron as B	88	40 - 265	86
Barium as Ba	14	<10 - 313	27
Mercury as Hg	.071	<.005 - .189	.057
Lead as Pb	27	9 - 376	26
Bismuth as Bi	<10	<10 - 37	14
Sulphate as SO_4	20,100	13,200 - 165,000	67,146
Carbonate as CO_3	18,000	<1,000 - 18,000	<3,877

PART C

MANITOUWADGE AREA

The analytical results that follow are based on representative tailings samples taken at two Manitouwadge area tailings deposits. These deposits contain an aggregate total of over 25,000,000 tons of mineral tailings.

Sample Code	3B33	3B34	Typical Composition
Production Commenced	1957	1957	-
Sodium as Na	6,640	8,130	7,385
Magnesium as Mg	10,100	7,730	8,915
Nitrogen as N	33.6	16.8	25
Fluorine as F	372	380	376
Aluminum as Al	25,000	32,200	28,600
Phosphorus as P	250	400	325
Chlorine as Cl	380	25	25
Potassium as K	15,300	10,100	12,700
Calcium as Ca	2,690	793	1,742
Titanium as Ti	990	700	845
Vanadium as V	<40	<40	<40
Chromium as Cr	48	50	49
Manganese as Mn	866	357	612
Iron as Fe	123,000	110,000	116,500
Cobalt as Co	21	3	12
Nickel as Ni	<10	<10	<10
Copper as Cu	558	1,110	834
Zinc as Zn	4,220	4,940	4,580
Arsenic as As	173	20	97
Selenium as Se	58	<1	<58
Strontium as Sr	61	62	61
Molybdenum as Mo	<0.6	<0.6	<0.6
Cadmium as Cd	7.5	1.9	4.7
Tin as Sn	181	180	180
Antimony as Sb	180	180	180
Boron as B	104	103	103
Barium as Ba	27	24	26
Mercury as Hg	.045	.029	.037
Lead as Pb	272	226	249
Bismuth as Bi	<10	<10	<10
Sulphate as SO_4	30,700	52,200	41,450
Carbonate as CO_3	<1,000	<1,000	<1,000

PART D

NORTHWESTERN ONTARIO AREAS

The analytical results quoted here are based on representative tailings samples taken from three tailings areas in northwestern Ontario. The specific properties sampled contain over 4,000,000 tons of mineral tailings. Several small properties were not sampled.

Sample Code	T20	YY	3B23
Production Commenced	1962	1971	1976
Sodium as Na	2,360	6,500	4,910
Magnesium as Mg	33,100	4,040	13,000
Nitrogen as N	55.8	33.4	11.1
Fluorine as F	233	413	296
Aluminum as Al	8,760	23,000	9,320
Phosphorus as P	264	709	270
Chlorine as Cl	55	17	50
Potassium as K	2,460	5,120	4,320
Calcium as Ca	9,350	98.5	2,360
Titanium as Ti	1,080	79	1,410
Vanadium as V	473	226	353
Chromium as Cr	285	39	147
Manganese as Mn	689	1,840	1,300
Iron as Fe	105,000	183,000	156,000
Cobalt as Co	187	274	33
Nickel as Ni	3,200	<10	4,080
Copper as Cu	571	5,390	18,700
Zinc as Zn	68.9	46,300	285
Arsenic as As	79	7,060	137
Selenium as Se	3	100	20
Strontium as Sr	21	26	30
Molybdenum as Mo	2.2	<0.6	<0.6
Cadmium as Cd	2.1	155	3.9
Tin as Sn	142	127	179
Antimony as Sb	236	266	160
Boron as B	84	85	58
Barium as Ba	10	20	43
Mercury as Hg	.179	<.005	.040
Lead as Pb	15	6,380	4
Bismuth as Bi	<10	108	<10
Sulphate as SO_4	72,900	52,900	126,000
Carbonate as CO_3	2,000	<1,000	<1,000

Sample Code	Data Range	Typical Composition
Production Commenced	-	-
Sodium as Na	2,360 - 6,500	4,590
Magnesium as Mg	4,040 - 33,100	16,713
Nitrogen as N	11.1 - 55.8	33
Fluorine as F	233 - 413	314
Aluminum as Al	8,760 - 23,000	13,693
Phosphorus as P	264 - 709	414
Chlorine as Cl	17 - 55	41
Potassium as K	2,460 - 5,120	3,967
Calcium as Ca	98.5 - 9,350	3,936
Titanium as Ti	79 - 1,410	856
Vanadium as V	226 - 473	351
Chromium as Cr	39 - 285	157
Manganese as Mn	689 - 1,840	1,276
Iron as Fe	105,000 - 183,000	148,000
Cobalt as Co	33 - 274	165
Nickel as Ni	<10 - 4,080	3,640
Copper as Cu	571 - 18,700	8,220
Zinc as Zn	68.9 - 46,300	177
Arsenic as As	79 - 7,060	108
Selenium as Se	3 - 100	41
Strontium as Sr	21 - 30	26
Molybdenum as Mo	<0.6 - 2.2	1
Cadmium as Cd	2.1 - 155	3
Tin as Sn	127 - 179	149
Antimony as Sb	160 - 266	221
Boron as B	58 - 85	76
Barium as Ba	10 - 43	24
Mercury as Hg	<.005 - .179	.075
Lead as Pb	4 - 6,380	10
Bismuth as Bi	<10 - 108	43
Sulphate as SO_4	52,900-126,000	83,933
Carbonate as CO_3	<1,000 - 2,000	1,333

PART E

SOUTHEASTERN ONTARIO

The analytical results quoted here are based on a single sample of mineral tailings taken from a small tailings deposit in southeastern Ontario. The deposit was estimated to contain less than 100,000 tons of tailings.

Sample Code	N
Production Commenced	
Sodium as Na	1,380
Magnesium as Mg	3,250
Nitrogen as N	<2.8
Fluorine as F	332
Aluminum as Al	8,190
Phosphorus as P	117
Chlorine as Cl	33
Potassium as K	5,130
Calcium as Ca	15,300
Titanium as Ti	98
Vanadium as V	<40
Chromium as Cr	49
Manganese as Mn	730
Iron as Fe	4,730
Cobalt as Co	<1
Nickel as Ni	<10
Copper as Cu	20
Zinc as Zn	9,050
Arsenic as As	149
Selenium as Se	<1
Strontium as Sr	41
Molybdenum as Mo	<0.6
Cadmium as Cd	18.3
Tin as Sn	230
Antimony as Sb	898
Boron as B	116
Barium as Ba	14
Mercury as Hg	.064
Lead as Pb	6,900
Bismuth as Bi	10
Sulphate as SO_4	9,630
Carbonate as CO_3	335,000

APPENDIX D

ANALYTICAL RESULTS

MINERAL TAILINGS

IRON OPERATIONS

PART A

NORTHEASTERN ONTARIO

The analytical results quoted here are based on two representative tailings samples taken at one iron property in northeastern Ontario. These samples represent more than 27,000,000 tons of tailings.

Sample Code	D	E	Typical Composition
Production Commenced	1968	1968	-
Sodium as Na	1,890	3,800	2,845
Magnesium as Mg	12,100	20,000	16,050
Nitrogen as N	2.8	5.6	4.2
Fluorine as F	122	121	122
Aluminum as Al	14,000	11,500	12,750
Phosphorus as P	286	498	392
Chlorine as Cl	<10	<10	<10
Potassium as K	3,480	3,100	3,290
Calcium as Ca	3,680	7,300	5,490
Titanium as Ti	71	72	72
Vanadium as V	199	160	180
Chromium as Cr	99	160	130
Manganese as Mn	816	1,290	1,053
Iron as Fe	100,000	90.800	95,400
Cobalt as Co	14	6	10
Nickel as Ni	427	78	253
Copper as Cu	50	30	40
Zinc as Zn	79.6	90.0	85
Arsenic as As	249	130	190
Selenium as Se	<1	<1	<1
Strontium as Sr	47	95	71
Molybdenum as Mo	<0.6	0.6	<0.6
Cadmium as Cd	1.4	1.0	1.2
Tin as Sn	63	107	85
Antimony as Sb	132	156	144
Boron as B	295	235	265
Barium as Ba	14	43	29
Mercury as Hg	.040	.047	.044
Lead as Pb	8	19	14
Bismuth as Bi	10	<10	<10
Sulphate as SO_4	65,500	8,950	37,225
Carbonate as CO_3	<1,000	<1,000	<1,000

PART B

NORTHWESTERN ONTARIO

The following analytical results are based on one representative sample of mineral tailings taken at an iron operation in northwestern Ontario. The sample represents over 10,000,000 tons of mineral tailings.

Sample Code	XX
Production Commenced	1968
Sodium as Na	11,400
Magnesium as Mg	6,220
Nitrogen as N	41.8
Fluorine as F	347
Aluminum as Al	23,200
Phosphorus as P	598
Chlorine as Cl	17
Potassium as K	18,800
Calcium as Ca	3,260
Titanium as Ti	1,330
Vanadium as V	85
Chromium as Cr	79
Manganese as Mn	306
Iron as Fe	145,000
Cobalt as Co	6
Nickel as Ni	38
Copper as Cu	39
Zinc as Zn	39.5
Arsenic as As	58
Selenium as Se	10
Strontium as Sr	124
Molybdenum as Mo	<0.6
Cadmium as Cd	1.5
Tin as Sn	73
Antimony as Sb	191
Boron as B	81
Barium as Ba	10
Mercury as Hg	<.005
Lead as Pb	11
Bismuth as Bi	35
Sulphate as SO_4	18,900
Carbonate as CO_3	<1,000

APPENDIX E

ANALYTICAL RESULTS

MINERAL TAILINGS

URANIUM OPERATIONS

PART A

BANCROFT AREA, ONTARIO

The analytical results quoted here are based on representative tailings samples taken at three uranium properties in the Bancroft area. Not all properties were sampled. These samples represent at least 5,700,000 tons of mineral tailings.

Sample Code	H	K	3B18
Production Commenced	1957	1942	1957
Sodium as Na	26,800	40,600	26,500
Magnesium as Mg	6,360	100	7,190
Nitrogen as N	36.2	22.2	50.1
Fluorine as F	2,520	157	1,200
Aluminum as Al	32,700	28,600	25,800
Phosphorus as P	830	162	910
Chlorine as Cl	<10	<10	50
Potassium as K	32,300	44,600	17,700
Calcium as Ca	4,970	99.0	374
Titanium as Ti	2,250	134	2,650
Vanadium as V	119	80	158
Chromium as Cr	209	28	89
Manganese as Mn	1,261	30	985
Iron as Fe	48,400	2,770	57,100
Cobalt as Co	3	<1	17
Nickel as Ni	<10	154	64
Copper as Cu	50	20	39
Zinc as Zn	218	<10	148
Arsenic as As	278	208	621
Selenium as Se	<1	<1	<1
Strontium as Sr	177	32	207
Molybdenum as Mo	2.2	<0.6	1.1
Cadmium as Cd	1.6	0.3	1.0
Tin as Sn	77	19	163
Antimony as Sb	78	86	190
Boron as B	104	115	84
Barium as Ba	21	21	20
Mercury as Hg	<.005	.059	.053
Lead as Pb	49	53	115
Bismuth as Bi	12	<10	<10
Sulphate as SO_4	16,300	3,610	38,300
Carbonate as CO_3	<1,000	<1,000	<1,000

Sample Code	Data Range	Typical Composition
Production Commenced	-	-
Sodium as Na	26,500 - 40,600	31,300
Magnesium as Mg	100 - 7,190	4,550
Nitrogen as N	22.2 - 50.1	36
Fluorine as F	157 - 2,520	1,292
Aluminum as Al	25,800 - 32,700	29,033
Phosphorus as P	162 - 910	634
Chlorine as Cl	<10 - 50	23
Potassium as K	17,700 - 44,600	31,533
Calcium as Ca	99 - 4,970	1,814
Titanium as Ti	134 - 2,650	1,678
Vanadium as V	80 - 158	119
Chromium as Cr	28 - 209	109
Manganese as Mn	30 - 1,261	759
Iron as Fe	2,770 - 57,100	36,090
Cobalt as Co	<1 - 17	7
Nickel as Ni	<10 - 154	76
Copper as Cu	20 - 50	36
Zinc as Zn	<10 - 218	125
Arsenic as As	208 - 621	369
Selenium as Se	-	<1
Strontium as Sr	32 - 207	139
Molybdenum as Mo	<0.6 - 2.2	1.3
Cadmium as Cd	0.3 - 1.6	1
Tin as Sn	19 - 163	86
Antimony as Sb	78 - 190	118
Boron as B	84 - 115	101
Barium as Ba	20 - 21	21
Mercury as Hg	<.005 - .059	.039
Lead as Pb	49 - 115	72
Bismuth as Bi	<10 - 12	11
Sulphate as SO_4	3,610 - 38,300	19,403
Carbonate as CO_3	-	<1,000

PART B

ELLIOT LAKE AREA

The following analytical results are based on one representative mineral tailings sample taken at one uranium property in the Elliot Lake area. Several major properties were not sampled. The sample noted here represents over 13,000,000 tons of mineral tailings.

NOTE: Since only one sample was taken in the Elliot Lake uranium camp, the data presented here may not be representative of the camp as a whole.

Sample Code	Y25
Production Commenced	1957
Sodium as Na	1,170
Magnesium as Mg	783
Nitrogen as N	75.4
Fluorine as F	225
Aluminum as Al	19,600
Phosphorus as P	48
Chlorine as Cl	10
Potassium as K	28,000
Calcium as Ca	97.8
Titanium as Ti	97
Vanadium as V	40
Chromium as Cr	20
Manganese as Mn	<10
Iron as Fe	11,100
Cobalt as Co	<1
Nickel as Ni	<10
Copper ad Cu	39
Zinc as Zn	9.8
Arsenic as As	137
Selenium as Se	<1
Strontium as Sr	21
Molybdenum as Mo	2.7
Cadmium as Cd	0.3
Tin as Sn	18
Antimony as Sb	97
Boron as B	107
Barium as Ba	205
Mercury as Hg	-
Lead as Pb	23
Bismuth as Bi	<10
Sulphate as SO_4	14,000
Carbonate as CO_3	<1,000

APPENDIX F

ANALYTICAL RESULTS

MINERAL TAILINGS

CORUNDUM OPERATIONS

PART A

BANCROFT AREA, ONTARIO

The analytical results quoted here are based on one representative tailings sample taken at one small corundum operation in the Bancroft area. The sample represents less than 100,000 tons of tailings.

Sample Code	P
Production Commenced	1900
Sodium as Na	46,600
Magnesium as Mg	2,480
Nitrogen as N	36.3
Fluorine as F	270
Aluminum as Al	95,700
Phosphorus as P	38.0
Chlorine as Cl	<10
Potassium as K	34,000
Calcium as Ca	12,900
Titanium as Ti	281
Vanadium as V	40
Chromium as Cr	30
Manganese as Mn	377
Iron as Fe	31,600
Cobalt as Co	8
Nickel as Ni	<10
Copper as Cu	30
Zinc as Zn	377
Arsenic as As	258
Selenium as Se	<1
Strontium as Sr	385
Molybdenum as Mo	<0.6
Cadmium as Cd	1.4
Tin as Sn	77
Antimony as Sb	309
Boron as B	21
Barium as Ba	56
Mercury as Hg	<.005
Lead as Pb	57
Bismuth as Bi	<10
Sulphate as SO_4	9,240
Carbonate as CO_3	<1,000

APPENDIX G

TYPICAL CHEMICAL CHARACTERISTICS
OF MINERAL TAILINGS IN ONTARIO:

A Gold Camps
B Silver Camps
C Base Metal Sulphide Camps
D Iron Mining Areas
E Uranium Camps

P A R T A

Gold Operations

TYPICAL

CHEMICAL CHARACTERISTICS OF MINERAL TAILINGS IN ONTARIO GOLD CAMPS

Gold Camp	Timmins Area	Kirkland & Larder Lakes	Red Lake	Wawa - Missanabie
Sodium as Na	5,076	18,100	low 1,662 high 20,760	13,123
Magnesium as Mg	10,348	7,333	11,229	4,353
Nitrogen as N	62	60	31	88
Fluorine as F	230	305	327	247
Aluminum as Al	23,630	30,743	32,278	26,375
Phosphorus as P	464	956	542	899
Chlorine as Cl	21	low 14 high 140	41	25
Potassium as K	12,504	low 6,888 high 40,875	14,258	18,438
Calcium as Ca	5,427	3,245	3,889	2,750
Titanium as Ti	100	318	726	320
Vanadium as V	148	194	117	99
Chromium as Cr	156	140	71	133
Manganese as Mn	801	671	940	496
Iron as Fe	51,464	45,236	47,760	56,200
Cobalt as Co	28	27	22	31
Nickel as Ni	70	low 35 high 304	93	<34
Copper as Cu	low 71 high 1,371	98	59	91
Zinc as Zn	low 169 high 3,110	94	162	89
Arsenic as As	1,668	low 249 high 6,225	4,176	672
Selenium as Se	3.5	low 2.1 high 11	2.4	<3
Strontium as Sr	38	221	80	124
Molybdenum as Mo	<0.6	4	<1.1	1.6
Cadmium as Cd	4	.8	1.8	.8
Tin as Sn	89	103	67	98
Antimony as Sb	329	192	309	232
Boron as B	91	84	99	81
Barium as Ba	14	13	17	13
Mercury as Hg	.166	1.03	.287	.417
Lead as Pb	low 25 high 2,078	23	25	32
Bismuth as Bi	<14	<11	<10	<10
Sulphate as SO_4	38,627	45,845	34,530	27,575
Carbonate as CO_3	low 2,500 high 47,400	8,200	3,333	<4,867

TYPICAL CHEMICAL CHARACTERISTICS OF MINERAL TAILINGS IN ONTARIO GOLD CAMPS

Gold Camp	Pickle L. Central Patricia	Geraldton-Beardmore	Uchi L. Confed. L.	Mata-chewan Area
Sodium as Na	4,021	14,090	9,960	23,550
Magnesium as Mg	14,933	6,954	9,595	4,178
Nitrogen as N	34	72	low 5.8 high 373	42
Fluorine as F	192	207	252	291
Aluminum as Al	15,933	30,450	24,050	54,025
Phosphorus as P	low 272 high 1,952	1,352	482	818
Chlorine as Cl	26	27	19	23
Potassium as K	4,350	11,033	13,800	57,350
Calcium as Ca	5,022	3,985	4,955	2,883
Titanium as Ti	214	180	low 220 high 1,580	183
Vanadium as V	108	137	123	125
Chromium as Cr	96	127	107	100
Manganese as Mn	824	463	701	481
Iron as Fe	low 53,875 high 223,800	52,871	61,400	32,600
Cobalt as Co	12	16	23	7
Nickel as Ni	<22	105	low <10 high 365	low 71 high 303
Copper as Cu	122	79	74	low 24 high 166
Zinc as Zn	182	120	181	low 84 high 1,000
Arsenic as As	low 337 high 5,664	8,852	low 58 high 525	292
Selenium as Se	<4	<1	<1	<2
Strontium as Sr	49	128	83	60
Molybdenum as Mo	<0.6	<0.6	.9	<.7
Cadmium as Cd	2	1.9	1.4	1.7
Tin as Sn	170	111	90	56
Antimony as Sb	363	187	214	208
Boron as B	101	93	102	87
Barium as Ba	24	24	25	30
Mercury as Hg	.222	.672	.269	.086
Lead as Pb	43	low 3.8 high 35	11	low 17 high 1,010
Bismuth as Bi	<10	<10	<10	<12
Sulphate as SO_4	45,656	12,747	13,600	37,850
Carbonate as CO_3	<1,629	17,000	14,400	low 9,000 high 45,000

TYPICAL CHEMICAL CHARACTERISTICS OF MINERAL TAILINGS IN ONTARIO GOLD CAMPS

	Typical Composition for ONTARIO Gold Tailings
Sodium as Na	12,560
Magnesium as Mg	8,615
Nitrogen as N	56
Fluorine as F	256
Aluminum as Al	29,686
Phosphorus as P	788
Chlorine as Cl	26
Potassium as K	12,397
Calcium as Ca	4,020
Titanium as Ti	219
Vanadium as V	131
Chromium as Cr	116
Manganese as Mn	672
Iron as Fe	49,647
Cobalt as Co	21
Nickel as Ni	65
Copper as Cu	87
Zinc as Zn	138
Arsenic as As	low 356 high 5,317
Selenium as Se	<2.4
Strontium as Sr	98
Molybdenum as Mo	<1.3
Cadmium as Cd	1.8
Tin as Sn	98
Antimony as Sb	254
Boron as B	92
Barium as Ba	20
Mercury as Hg	.4
Lead as Pb	low 26 high 1,544
Bismuth as Bi	11
Sulphate as SO_4	32,054
Carbonate as CO_3	7,616

P A R T B

Silver Operations

TYPICAL CHEMICAL CHARACTERISTICS OF MINERAL TAILINGS IN ONTARIO SILVER CAMPS

Silver Camp	Cobalt Area	Gowganda Area	Typical Composition Ontario Silver Tailings
Sodium as Na	27,113	8,050	17,581
Magnesium as Mg	9,113	10,225	9,669
Nitrogen as N	48	42	45
Fluorine as F	257	292	275
Aluminum as Al	40,995	19,900	30,448
Phosphorus as P	1,155	524	840
Chlorine as Cl	<13	17	<15
Potassium as K	8,779	10,625	9,702
Calcium as Ca	4,406	4,965	4,686
Titanium as Ti	1,038	866	952
Vanadium as V	216	181	199
Chromium as Cr	151	238	195
Manganese as Mn	644	1,054	849
Iron as Fe	50,121	57,550	53,836
Cobalt as Co	426	363	395
Nickel as Ni	166	190	178
Copper as Cu	309	112	211
Zinc as Zn	314	107	211
Arsenic as As	4,275	7,665	5,970
Selenium as Se	<1.3	2	<1.7
Strontium as Sr	59	30	45
Molybdenum as Mo	<1.1	1.4	1.3
Cadmium as Cd	1.5	1.2	1.4
Tin as Sn	74	61	68
Antimony as Sb	267	185	226
Boron as B	95	81	88
Barium as Ba	34	15	25
Mercury as Hg	1.335	.972	1.2
Lead as Pb	101	27	64
Bismuth as Bi	26	18	22
Sulphate as SO_4	12,714	16,050	14,382
Carbonate as CO_3	5,203	9,000	7,102

P A R T C

Base Metal Sulphide Operations

(Cu, Ni, Pb, Zn)

TYPICAL CHEMICAL CHARACTERISTICS OF MINERAL TAILINGS IN ONTARIO BASE METAL SULPHIDE CAMPS

Base Metal Sulphide Camp	Timmins Kirkland Lake Areas	S.S. Marie Sudbury Temagami Areas	Manitou wadge Area	North western Ontario Areas
Sodium as Na	2,413	9,141	7,385	4,590
Magnesium as Mg	17,358	12,650	8,915	16,713
Nitrogen as N	47	30	25	33
Fluorine as F	224	275	376	314
Aluminum as Al	24,315	27,521	28,600	13,693
Phosphorus as P	220	443	325	414
Chlorine as Cl	17	<15	25	41
Potassium as K	8,145	8,429	12,700	3,967
Calcium as Ca	3,102	4,612	1,742	3,936
Titanium as Ti	539	1,323	845	856
Vanadium as V	98	194	<40	351
Chromium as Cr	114	249	49	157
Manganese as Mn	636	676	612	1,276
Iron as Fe	153,500	89,127	116,500	148,000
Cobalt as Co	90	80	12	165
Nickel as Ni	64	1,983	<10	3,640
Copper as Cu	639	519	834	8,220
Zinc as Zn	2,789	164	4,580	177
Arsenic as As	667	232	97	108
Selenium as Se	63	8	<58	41
Strontium as Sr	126	103	61	26
Molybdenum as Mo	2.5	<1	<0.6	1
Cadmium as Cd	8	2.3	4.7	3
Tin as Sn	137	125	180	149
Antimony as Sb	196	292	180	221
Boron as B	93	86	103	76
Barium as Ba	34	27	26	24
Mercury as Hg	.262	.057	.037	.075
Lead as Pb	44	26	249	10
Bismuth as Bi	43	14	<10	43
Sulphate as SO_4	140,775	67,146	41,450	83,933
Carbonate as CO_3	<1,250	<3,877	<1,000	1,333

TYPICAL COMPOSITION FOR ONTARIO BASE METAL SULPHIDE

(Cu, Ni, Pb, Zn) TAILINGS

Sodium as Na	5,882
Magnesium as Mg	13,909
Nitrogen as N	34
Fluorine as F	297
Aluminum as Al	23,532
Phosphorus as P	351
Chlorine as Cl	25
Potassium as K	8,310
Calcium as Ca	3,348
Titanium as Ti	891
Vanadium as V	171
Chromium as Cr	142
Manganese as Mn	800
Iron as Fe	126,781
Cobalt as Co	87
Nickel as Ni	Where nickel is ore mineral 2,812; otherwise <37
Copper as Cu	664
Zinc as Zn	Where zinc is ore mineral 3,685; otherwise 171
Arsenic as As	276
Selenium as Se	<43
Strontium as Sr	79
Molybdenum as Mo	<1.3
Cadmium as Cd	4.5
Tin as Sn	148
Antimony as Sb	222
Boron as B	90
Barium as Ba	28
Mercury as Hg	.1
Lead as Pb	82
Bismuth as Bi	28
Sulphate as SO_4	83,326
Carbonate as CO_3	<1,865

P A R T D

Iron Operations

TYPICAL CHEMICAL CHARACTERISTICS OF MINERAL TAILINGS IN ONTARIO IRON MINING AREAS

Iron Mining Area	North eastern Ontario	North western Ontario	Typical Composition for ONTARIO Iron Tailings
Sodium as Na	2,845	11,400	7,123
Magnesium as Mg	16,050	6,220	11,135
Nitrogen as N	4.2	41.8	23
Fluorine as F	122	347	235
Aluminum as Al	12,750	23,200	17,975
Phosphorus as P	392	598	495
Chlorine as Cl	<10	17	<14
Potassium as K	3,290	18,800	11,045
Calcium as Ca	5,490	3,260	4,375
Titanium as Ti	72	1,330	701
Vanadium as V	180	85	133
Chromium as Cr	130	79	105
Manganese as Mn	1,053	306	680
Iron as Fe	95,400	145,000	120,200
Cobalt as Co	10	6	8
Nickel as Ni	253	38	146
Copper as Cu	40	39	40
Zinc as Zn	85	39.5	62
Arsenic as As	190	58	124
Selenium as Se	<1	10	6
Strontium as Sr	71	124	98
Molybdenum as Mo	<0.6	<0.6	<0.6
Cadmium as Cd	1.2	1.5	1.4
Tin as Sn	85	73	79
Antimony as Sb	144	191	168
Boron as B	265	81	173
Barium as Ba	29	10	20
Mercury as Hg	.044	<.005	.03
Lead as Pb	14	11	13
Bismuth as Bi	<10	35	23
Sulphate as SO_4	37,225	18,900	28,063
Carbonate as CO_3	<1,000	<1,000	<1,000

PART E

Uranium Operations

TYPICAL CHEMICAL CHARACTERISTICS OF MINERAL TAILINGS IN ONTARIO URANIUM MINING AREAS

Uranium Camp	Bancroft Camp	Elliot Lake Camp	Typical Composition ONTARIO Uranium Tailings
Sodium as Na	31,300	1,170	
Magnesium as Mg	4,550	783	
Nitrogen as N	36	75.4	
Fluorine as F	1,292	225	Bancroft and Elliot
Aluminum as Al	29,033	19,600	Lake uranium deposits
Phosphorus as P	634	48	differ greatly in
Chlorine as Cl	23	10	geology and mineral-
Potassium as K	31,533	28,000	ogy, also, the
Calcium as Ca	1,814	97.8	mining methods used
Titanium as Ti	1,678	97	in each camp differ
Vanadium as V	119	40	substantially.
Chromium as Cr	109	20	Therefore, a
Manganese as Mn	759	<10	"Typical ONTARIO
Iron as Fe	36,090	11,100	Composition"
Cobalt as Co	7	<1	has little meaning.
Nickel as Ni	76	<10	
Copper as Cu	36	39	
Zinc as Zn	125	9.8	
Arsenic as As	369	137	
Selenium as Se	<1	<1	
Strontium as Sr	139	21	
Molybdenum as Mo	1.3	2.7	
Cadmium as Cd	1	0.3	
Tin as Sn	86	18	
Antimony as Sb	118	97	
Boron as B	101	107	
Barium as Ba	21	205	
Mercury as Hg	.039	-	
Lead as Pb	72	23	
Bismuth as Bi	11	<10	
Sulphate as SO_4	19,403	14,000	
Carbonate as CO_3	<1,000	<1,000	

NOTE: Elliot Lake data based on one sample only.

APPENDIX H

GENERAL CHEMICAL CHARACTERISTICS

OF MINERAL TAILINGS

IN ONTARIO MINING CAMPS

TYPICAL CHEMICAL CHARACTERISTICS OF MINERAL TAILINGS

IN ONTARIO MINING CAMPS

Mining Camp	Gold	Silver	Base Metal Sulphide (Cu,Ni,Pb,Zn)	Iron
Sodium as Na	12,560	17,581	5,882	7,123
Magnesium as Mg	8,615	9,669	13,909	11,135
Nitrogen as N	56	45	34	23
Fluorine as F	256	275	297	235
Aluminum as Al	29,686	30,448	23,532	17,975
Phosphorus as P	788	840	351	495
Chlorine as Cl	26	<15	25	<14
Potassium as K	12,397	9,702	8,310	11,045
Calcium as Ca	4,020	4,686	3,348	4,375
Titanium as Ti	219	952	891	701
Vanadium as V	131	199	171	133
Chromium as Cr	116	195	142	105
Manganese as Mn	672	849	800	680
Iron as Fe	49,647	53,836	126,781	120,000
Cobalt as Co	21	395	87	8
Nickel as Ni	65	178	low <37 high 2,812	146
Copper as Cu	87	211	664	40
Zinc as Zn	138	211	low 171 high 3,685	62
Arsenic as As	low 356 high 5,317	5,970	276	124
Selenium as Se	<2.4	<1.7	<43	6
Strontium as Sr	98	45	79	98
Molybdenum as Mo	<1.3	1.3	<1.3	<0.6
Cadmium as Cd	1.8	1.4	4.5	1.4
Tin as Sn	98	68	148	79
Antimony as Sb	254	226	222	168
Boron as B	92	88	90	173
Barium as Ba	20	25	28	20
Mercury as Hg	.4	1.2	.1	.03
Lead as Pb	low 26 high 1,544	64	82	13
Bismuth as Bi	11	22	28	23
Sulphate as SO_4	32,054	14,382	83,326	28,063
Carbonate as CO_3	7,616	7,102	<1,865	<1,000

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